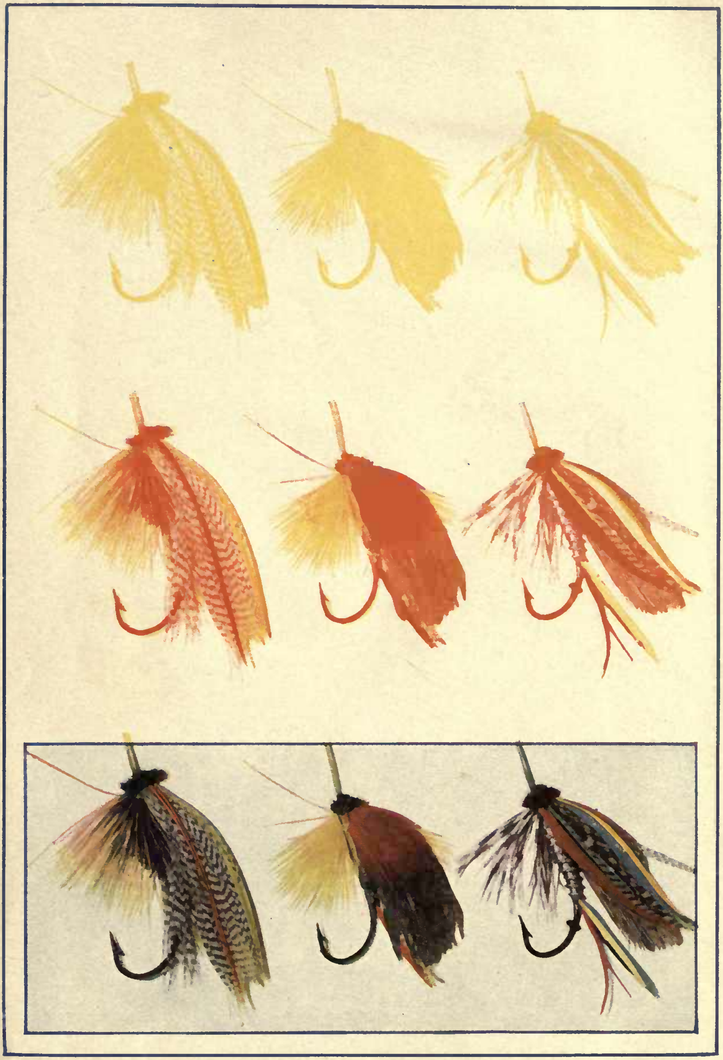

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(*See page 236*)

FIRST PRINCIPLES
OF
PHYSICS

BY Green

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PREFACE

Not many years ago the ideal textbook in elementary physics was little more than a concise, scientific statement of the fundamental principles of the subject, illustrated by experiments and reënforced by numerous problems designed to emphasize the expression of physical relations in mathematical form. Teachers, however, came to recognize that books of this type do not make the subject sufficiently attractive to pupils who are familiar with picturesque, popular applications of physics, and who are not inclined to devote the requisite time and effort to overcome the difficulties of a less alluring side of the subject.

Attempts have been made to meet this vague dissatisfaction by presenting many familiar illustrations of the practical applications of physics, but with an unsatisfactory treatment of the fundamental principles on which these applications are based. As a result, pupils reached the end of their study with few definite ideas and little knowledge of the science itself. This condition was plainly so much worse than the former one that teachers, who have been drawn into the experiment, have generally preferred to return to the earlier type of book.

The present volume is the result of an attempt to make a book which shall have a strong element of interest and attractiveness, and at the same time be so clear and definite in the treatment of principles that pupils may carry away from the course some useful acquisitions for daily life and a preparation for continuing the subject with success in the college or technical school. Every effort has been made to have the language of the book clear and simple. Cordial acknowledgment is made to many teachers whose helpful criticisms have been an aid to

this end. The problems given require for their solution only such simple algebraic operations as offer no difficulty to pupils who have taken a course in elementary algebra.

Yielding to the advice of teachers in whose judgment the authors have the greatest confidence, a somewhat radical change has been made in the order of subjects by placing the Mechanics of Fluids before the Mechanics of Solids. The reason assigned is that the facts and principles of the former are more familiar than those of the latter; they thus form a natural approach to the abstract laws of motion, the composition and resolution of forces and velocities, and the formulæ connected with them as the shorthand expression of physical laws.

H. S. C.

H. N. C.

April, 1912.

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FIRST PRINCIPLES OF PHYSICS

CHAPTER I

INTRODUCTION

I. MATTER AND ENERGY

1. Physics Defined. — *Physics* is often defined as *the science of matter and energy. Matter* is everything we can see, taste, or touch; such as air, water, earth, gas, wood, steam — in short, everything which *occupies space. Energy is the capacity for doing work*, that is, for producing any change in the position or condition of matter, especially against resistance opposing such a change. Water in an elevated tank, steam under pressure in a boiler, a flying cannon ball, — all have the capacity for doing work, overcoming resistance, or changing the position and motion of bodies.

So if everything which we recognize by the senses is *matter*, and every change in matter involves *energy*, it is plain that *physics*, which is *the science of matter and energy*, is a universal science, touching our life at every point. Whatever we see or touch is matter; whatever we do exhibits energy. Countless physical *phenomena* are taking place about us every day: a girl playing tennis, a boy rowing a boat, the school bell ringing, the sun giving light and heat, the wind flapping a sail, an apple falling from a tree, a train or an automobile whizzing by, — all are examples of matter and associated energy.

Physics is not so much concerned with matter alone or with energy alone as with the relations of the two. A baseball is of little interest in itself; it becomes interesting only in connection with a bat and the energy of the player's arm. The engine driver's interest is not so much in the engine itself as in the engine with steam up ready to drive it. No one would care to purchase an automobile to stand in a garage; its attractiveness lies in the fact that it becomes almost a living thing when its motor is vitalized by the heat of combustion of gasoline.

2. Physical Principles and their Applications. — The phenomena of physics appear in everything we see or do. It will be impossible to learn about all of them in a single year. This is especially true because the phenomena of physics, and in particular the *applications* of physical principles, are constantly changing. But the *principles*[1] *remain the same.* So this book lays emphasis on the *principles of physics* and their common applications, leaving it to the enthusiasm and ingenuity of both teacher and pupils to supplement the applications with illustrations drawn from life and from scientific and technical journals.

3. States of Matter. — Matter may exist in three states, exemplified by water, which may assume either the *solid*, the *liquid*, or the *gaseous* form. Ice, water, and water vapor may all exist together at the same temperature.

Briefly described,

Solids have definite size and shape.

Liquids have definite size, but the shape is that of the containing vessel.

[1] An *hypothesis* is a supposition which serves to explain *phenomena*. The more varied the phenomena it explains, the greater the probability of its truth. When the evidence in support of it becomes large, it is raised to the rank of a *theory;* and when its truth is fully established, it becomes a *law* or *principle*.

Gases have neither definite size nor shape, both depending on the containing vessel.

Some substances are neither wholly in the one state nor in the other. Sealing wax softens by heat and passes gradually from the solid to the liquid state. Shoemaker's wax breaks into fragments like a solid under the blow of a hammer, but under long-continued pressure it flows like a liquid, though slowly, and may be molded at will.

II. PROPERTIES OF MATTER

4. Properties General and Special. — The properties of matter are the qualities which serve to describe and define it. They are either *general*, that is, common to all kinds of matter; or *special*, that is, found in some kinds of matter but not in others. Thus, all matter has *extension*, or occupies space. On the other hand, a piece of common window glass lets light pass through it, or is *transparent*, while a piece of sheet iron does not transmit light, or is *opaque*. A watch spring recovers its shape after bending, or is *elastic*, while a strip of lead possesses this property in so slight a degree that it is classed as *inelastic*. So we see that while extension is a general property of matter, transparency and elasticity are special properties.

A. General Properties

5. Extension. — All bodies have three dimensions, length, breadth, and thickness. A sheet of tissue paper or of gold leaf, at first thought, appears to have but two dimensions, length and breadth; but while its third dimension is relatively small, if its thickness should actually become zero, it would cease to be either a sheet of paper or a piece of gold leaf. *Extension is the property of occupying space or having dimensions.*

6. Impenetrability. — Matter occupies space, but no two portions of matter can occupy the same space at the same time. The volume of an irregular solid, such as a lump of coal, may be measured by noting the volume of liquid displaced when the solid is completely immersed in it. *The general property of matter that no two bodies can occupy the same space at the same time is known as impenetrability.*

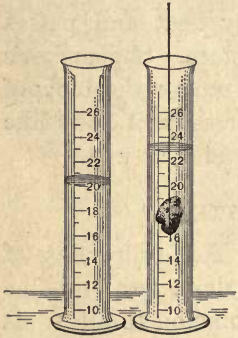


Fig. 1

Put a lump of coal into a tall graduate partly filled with water, as in Fig. 1. Note the reading at the surface of the water before and after putting in the coal; the difference is the volume of the water displaced, or that of the piece of coal.

7. Inertia. — The most characteristic general property of matter is *inertia. Inertia is the property which all matter possesses of resisting any attempt to start it if at rest, to stop it if in motion, or to change either the direction or the amount of its motion.* If a moving body stops, its arrest is always owing to something outside of itself; and if a body at rest is

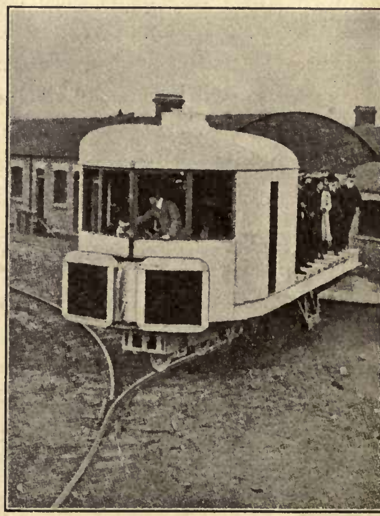


Fig. 2

set moving, motion must be imparted to it by some other body.

8. Illustrations of Inertia. — Many familiar facts are due to inertia. When a street car stops suddenly, a person standing continues by inertia to move forward, or is apparently thrown toward the front of the car; the driver of a racing motor car is apparently thrown with violence when the rapidly moving car collides with a post or a tree; the fact is the car is violently stopped, while the driver continues to move forward as before the collision. When a fireman shovels coal into a furnace, he suddenly arrests the motion of the shovel and leaves the coal to move forward by inertia. A smooth cloth may be snatched from under a heavy dish without disturbing it. The violent jar to a water pipe when a faucet is suddenly closed is accounted for by the inertia of the stream. The persistence with which a spinning top maintains its axis of rotation in the same direction is due to its inertia.

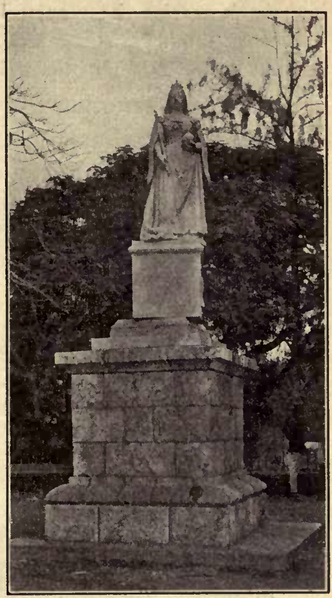


Fig. 3

Brennan's monorail car (Fig. 2) is kept in an upright position by the inertia of a rapidly revolving wheel of great weight. Tall columns, chimneys, and buildings are sometimes twisted around by violent earthquake movements (Fig. 3). The sudden circular motion of the earth under a column leaves it standing still, while the slower return motion carries it around.

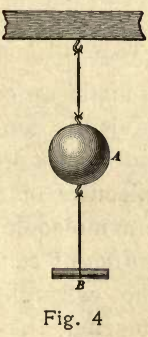


Fig. 4

Suspend a heavy weight by a cotton string, as in Fig. 4, and tie a piece of the same string to the under side of the weight. A *steady* downward pull at *B* will break the upper string

because it carries the greater load. A *sudden* downward pull on B will break the lower string before the pull reaches the upper one on account of the inertia of the weight.

9. Mass. — Another general property of matter is *mass.* We are all familiar with the fact that the less matter there is in a body, the more easily it is moved, and the more easily it is stopped when in motion. One can tell an empty barrel from a full one by a kick, a block of wood from a brick by shoving it with the foot, and a tennis ball from a baseball by catching it. *Mass is the measure of the resistance which a body offers to motion or change of motion;* it is therefore the measure of the body's inertia. Mass must not be confused with weight (§ 116) because mass is independent of gravity. The mass of a meteoric body is the same when flying through space as when it strikes the earth and embeds itself in the ground. If it could reach the center of the earth, its weight would become zero; at the surface of the sun it would weigh nearly twenty-eight times as much as at the earth's surface; but its mass would be the same everywhere. For this reason, and others which will appear later, in discussing the laws of physics we prefer to speak of *mass* when a student thinks the term *weight* might be used as well.

10. Cohesion and Adhesion. — All bodies are made up of very minute particles, which are separately invisible, and are called *molecules. Cohesion is the force of attraction between molecules*, and it binds together the molecules of a substance so as to form a larger mass than a molecule. *Adhesion is the force uniting bodies by their adjacent surfaces.* When two clean surfaces of white-hot wrought iron are brought into close contact by hammering, they *cohere* and become a single body. If a clean glass rod be dipped into water and then withdrawn, a drop will *adhere*

to it. Glue, adhesive plaster, and postage stamps stick by adhesion. Mortar adheres to bricks and gold plating to brass.

Suspend from one of the scalepans of a beam balance a clean glass disk by means of threads cemented to it (Fig. 5). After counterpoising the disk, place below it a vessel of water, and adjust so that the disk just touches the surface of the water when the beam of the balance is horizontal. Now add weights to the opposite pan until the disk is pulled away from the water. Note that the under surface of the disk is wet. The adhesion of the water to the glass is greater than the cohesion between the molecules of the water. If mercury be substituted for water, a much greater force will be necessary to separate the disk from the mercury, but no mercury will adhere to it. The force of cohesion between the molecules of the mercury is greater than the adhesion between it and the glass.

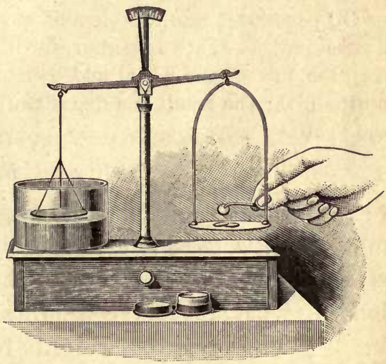


Fig. 5

Cut a fresh, smooth surface on two lead bullets and hold these surfaces gently together. They will not stick. Now press them tightly together with a slight twisting motion. They will *adhere* quite firmly. This fact shows that molecular forces act only through insensible distances. It has been shown that they vanish in water at a range of about one five-hundred-thousandth of an inch.

An interesting example of *selective adhesion* occurs in the winning of diamonds in South Africa. The mixed pebbles and other worthless stones, with an occasional diamond, are washed down an inclined shaking surface covered with grease. Only the diamonds and a few other precious stones stick to the grease; the rest are washed away.

11. Porosity. — Sandstone, unglazed pottery, and similar bodies absorb water without change in volume. The water

fills the small spaces called *pores*, which are visible either to the naked eye or under a microscope. All matter is probably porous, though the pores are invisible, and the corresponding property is called *porosity*. In a famous experiment in Florence many years ago, a hollow sphere of heavily gilded silver was filled with water and put under pressure. The water exuded through the pores of the silver and gold and stood in beads on the surface. Francis Bacon observed a similar phenomenon with a lead sphere.

Oil penetrates into marble and spreads through it. Even so dense a substance as agate is porous, for it is artificially colored by the absorption, first of one liquid and then of another which acts chemically on the first; the result is a deposit of coloring matter in the pores of the agate.

B. Special Properties

12. Tenacity and Tensile Strength. — *Tenacity is the resistance which a body offers to being torn apart.* The tensile strength of wires is tested by hanging them vertically and loading with successive weights until they break (Fig. 6).

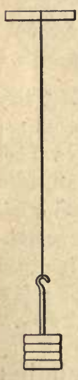


Fig. 6

The breaking weights for wires of different materials but of the same cross section differ greatly. A knowledge of tensile strength is essential in the design of telegraph wires and cables, suspension bridges, and the tension members of all steel structures.

Tenacity diminishes with the duration of the pull, so that wires sometimes break with a load which they have supported for a long time. Lead has the least tenacity of all solid metals, and cast steel the greatest. Even the latter is exceeded by fibers of silk and cotton. Single fibers of cotton can support millions of times their own weight.

13. Ductility. — *Ductility is the property of a substance which permits it to be drawn into wires or filaments.* Gold, copper, silver, and platinum are highly ductile. The last is the most ductile of all. It has been drawn into wire only 0.00003 inch in diameter. A mile of this wire would weigh only 1.25 grains.

Other substances are highly ductile only at high temperatures. Glass has been spun into such fine threads that a mile of it would weigh only one third of a grain. Melted quartz has been drawn into threads not more than 0.00001 inch in diameter. Such threads have nearly as great tenacity as steel.

14. Malleability. — *Malleability is a property which permits of hammering or rolling some metals into thin sheets.* Gold leaf, made by hammering between skins, is so thin that it is partially transparent and transmits green light. Zinc is malleable when heated to a temperature of from 100° to 150° C. (centigrade scale). It can then be rolled into sheets. Nickel at red heat can be worked like wrought iron. Malleable iron is made from cast iron by heating it for several days in contact with a substance which removes some of the carbon from the cast iron.

15. Hardness and Brittleness. — *Hardness is the resistance offered by a body to scratching by other bodies.* The relative hardness of two bodies is ascertained by finding which will scratch the other. Diamond is the hardest of all bodies because it scratches all others. Sir William Crookes has shown that diamonds under great hydraulic pressure between mild steel plates completely embed themselves in the metal. Carborundum, an artificial material used for grinding metals, is nearly as hard as diamond.

Brittleness is aptness to break under a blow. It must be

distinguished from hardness. Steel is hard and tough, while glass is hard and brittle.

Tool steel becomes glass hard and brittle when suddenly cooled from a high temperature. The *tempering* of steel is the process of giving the degree of hardness required for various purposes. It consists usually in first plunging the article at red heat into cold water or other liquid to give it an excess of hardness; then reheating gradually until the hardness is reduced, or "drawn down," to the required degree. The indication of the hardness is the color appearing on a polished portion, such as straw-yellow, brown-yellow, purple, or blue.

The process of *annealing* as applied to iron and glass is used to render them less brittle. It is done by cooling very slowly and uniformly from a high temperature. Soft iron is thus made more ductile, while glass is relieved from the molecular stresses set up in rapid cooling, and it thus becomes tougher and more uniform. The best lamp chimneys are annealed by the manufacturer. Disks of glass for telescope lenses must be carefully annealed to prevent fracture and warping during the process of grinding and polishing.

III. PHYSICAL MEASUREMENTS

16. Units. — To measure any physical quantity a certain fixed amount of the same kind of quantity is used as the *unit*. For example, to measure the length of a body, some arbitrary length, such as a foot, is chosen as the unit of length; *the length of a body is the number of times this unit is contained in the longest dimension of the body.* The unit is always expressed in giving the magnitude of any physical quantity; the other part of the expression is the numerical value. For example, 60 (feet), 500 (pounds), 45 (seconds).

In like manner, to measure a surface the unit, or standard surface, must be given, such as a square foot; and to measure a volume, the unit must be a given volume, such, for example, as a cubic inch, a quart, or a gallon.

17. Units of Length. — The two systems of units in common use are the *metric* and the *English*. In the former the unit of length is the meter. It is the distance

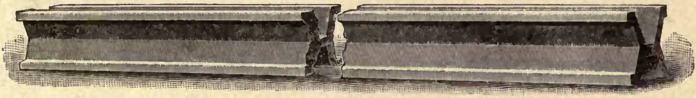


Fig. 7

between two transverse lines on each of two bars of platinum-iridium at the temperature of melting ice. These bars, called national prototypes, are preserved at the Bureau of Standards in Washington (Fig. 7).

The *meter* (m.) is divided into 10 *decimeters* (dm.), the decimeter into 10 *centimeters* (cm.), and the centimeter into 10 *millimeters* (mm.). The only multiple of the meter in general use is the *kilometer* (km.), equal to 1000 meters. It is used to measure such distances as are expressed in miles in the English system.

In the metric system areas are measured in square millimeters (mm.^{2}), square centimeters (cm.^{2}), etc. In like manner volumes are measured in cubic millimeters (mm.^{3}), cubic centimeters (cm.^{3}), etc. The cubic decimeter (dm.^{3}) is called a *liter* (l.); it is equal to 1000 cm.^{3}.

The weights and measures in common use in the United States were defined by Act of Congress in 1866 in terms of those of the metric system. By this act the legal value of the yard is $\frac{3600}{3937}$ of a meter; conversely, the meter is 39.37 inches. The inch is, therefore, 2.540 cm. The

relation between the centimeter scale and the inch scale is shown in Fig. 8.

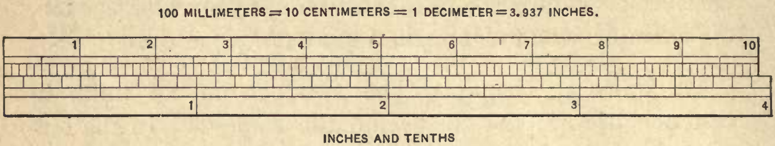


Fig. 8

The unit of length in the English system for the United States is the *yard*, defined as above. One third of the yard is the *foot*, and one thirty-sixth is the *inch*. The *gallon* of 231 cubic inches is the unit of volume for liquid measure. Tables for the conversion of quantities from one system of units into the other may be found in Appendix II.

18. Units of Mass. — The unit of mass in the metric system is the *kilogram* (kgm.). The United States has two prototype kilograms made of platinum-iridium and preserved at the Bureau of Standards in Washington (Fig. 9). The *gram* (gm.) is one thousandth of the kilogram. The latter was originally designed to represent the mass of a liter of pure water at 4° C. (centigrade scale). For practical purposes this is the kilogram. The gram is

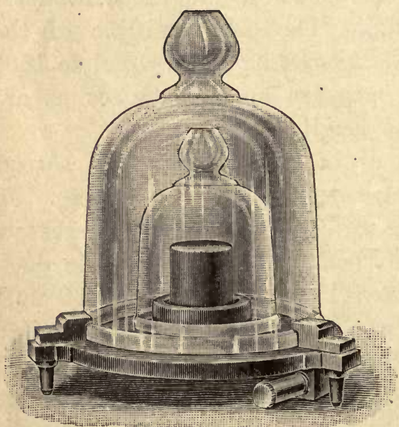


Fig. 9

therefore equal to the mass of a cubic centimeter of water at the same temperature. The mass of a given body of water can thus be immediately inferred from its volume.

The unit of mass in the English system is the *avoirdupois pound* (lb.). The *ton* of 2000 pounds is its chief multiple; its submultiples are the *ounce* (oz.) and the *grain* (gr.). The avoirdupois pound is equal to 16 ounces and to 7000 grains. The "troy pound of the mint" contains 5760 grains. In 1866 the mass of the 5-cent nickel piece was legally fixed at 5 grams; and in 1873 that of the silver half dollar at 12.5 grams. One gram is equal approximately to 15.432 grains. A kilogram is very nearly 2.2 pounds.

19. The Unit of Time. — The unit of time in universal use in physics is the *second*. It is $\frac{1}{86400}$ of a mean solar day. The number of seconds between the instant when the sun's center crosses the meridian of any place and the instant of its next passage over the same meridian is not uniform, chiefly because the motion of the earth in its orbit about the sun varies from day to day. The *mean solar day* is the average length of all the variable solar days throughout the year. It is divided into $24 \times 60 \times 60 = 86{,}400$ seconds of mean solar time, the time recorded by clocks and watches. The sidereal day used in astronomy is nearly four minutes shorter than the mean solar day.

20. The Three Fundamental Units. — Just as the measurement of areas and of volumes reduces simply to the measurement of lengths, so it has been found that the measurement of most other physical quantities, such as the speed of a ship, the pressure of water in the mains, the energy consumed by an electric lamp, and the horse power of an engine, may be made in terms of the units of

length, *mass*, and *time*. For this reason these three are considered *fundamental units* to distinguish them from all others, which are called *derived units*.

The system now in general use in the physical sciences employs the *centimeter* as the unit of length, the *gram* as the unit of mass, and the *second* as the unit of time. It is accordingly known as the *c. g. s.* (centimeter-gram-second) system.

Exercises and Problems

Problems involving the relations between the two systems of measurement should be solved, using the exact values of §§ 17 and 18.

1. Could the volume of a lump of sugar be determined by the method of § 6?

2. The circus rider standing on the back of a moving horse jumps straight up and not forward in order to go through a paper-covered hoop. Explain.

3. An ax handle is driven into the ax by pounding the end of the handle rather than the ax. Explain.

4. To keep from falling the conductor runs by the side of the moving car before he jumps on. Why?

5. A man standing on a moving car jumps vertically upward. Does he come down on the spot from which he jumped, or back of it?

6. Why will a bullet from a rifle shot at a window cut a smooth hole through the glass, but if thrown against it by hand shatter it?

7. Lead bullets fired from a rifle against a thick plate of lead are found welded to the plate. Why?

8. If a horse in starting a loaded wagon is permitted to jump, he is likely to break the harness; but if he pulls steadily, the harness is sufficient to stand the pull. Explain.

9. Why does the flywheel cause an engine to run more uniformly?

10. Why does a pendulum keep moving when the bob reaches the lowest point of its swing?

11. How many meters in a rod?

12. The Washington monument is 555 ft. high. Find its height in meters.

13. How many gallons in 100 liters?

14. Calculate the number of liters in 10 gal.

15. A motor boat has a speed of 20 mi. an hour. Express it in kilometers per hour.

16. At 10¢ per pound, what will be the cost of 10 kgm. of rice?

17. A cubic foot of water weighs 62.4 lb.; what is the weight of a cubic inch in grains?

18. A cubic foot of water weighs 62.4 lb.; what is the weight of a cubic inch in grams?

19. Find the difference in centimeters between one foot and 30 cm.

20. The greatest allowable weight of a package by foreign parcels post is 5 kgm. What is the nearest whole number of pounds?

CHAPTER II

MOLECULAR PHYSICS

I. MOLECULAR MOTION

21. Diffusion of Gases. — If two gases are placed in free communication with each other and are left undisturbed, they will mix rather rapidly. Even though they differ in density and the heavier gas is at the bottom, the mixing goes on. This process of the spontaneous mixing of gases is called *diffusion.*

The rapidity with which gases diffuse may be illustrated by allowing illuminating gas to escape into a room, or by exposing ammonia in an open dish. The odor quickly reveals the presence of either gas in all parts of the room, even when air currents are suppressed as far as possible. A more agreeable illustration is furnished by a bottle of smelling salts. If it is left open, the perfume soon pervades the whole room.

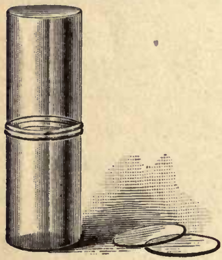


Fig. 10

Fill one of a pair of jars (Fig. 10) with the fumes of strong hydrochloric acid, and the other with gaseous ammonia, and place over them the glass covers. Bring the jars together as shown, and after a few seconds slip out the cover glasses. In a few minutes both jars will be filled with a white cloud of the chloride of ammonia. Instead of these vapors air and illuminating gas may be used, and after diffusion, the presence of an explosive mixture in both jars may be shown by applying a flame to the mouth of each separately.

22. Effusion through Porous Walls. — The passage of a gas through the pores of a solid is known as *effusion.* The rate of effusion for different gases is nearly inversely proportional to the square of their relative densities. Hydrogen, for example, which is one sixteenth as heavy as oxygen, passes through very small openings four times as fast as oxygen.

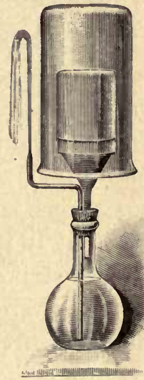


Fig. 11

Cement a small unglazed battery cup to a funnel tube, and connect the latter to a flask nearly filled with water and fitted with a jet tube, as shown in Fig. 11. Invert over the porous cup a large glass beaker or bell jar, and pass into it a stream of hydrogen or illuminating gas. If all the joints are air-tight, a small water jet will issue from the fine tube. The hydrogen passes freely through the invisible pores in the walls of the porous cup and produces gas pressure in the flask. If the beaker is now removed, the jet subsides and the pressure in the flask quickly falls to that of the air outside by the passage of hydrogen outward through the pores of the cup.

23. Molecular Motion in Gases. — The simple facts of the diffusion and effusion of gases lead to the conclusion that their molecules are not at rest, but are in constant and rapid motion. The property of indefinite expansibility is a further evidence of molecular motion in gases. No matter how far the exhaustion is carried by an air pump, the gas remaining in a closed vessel expands and fills it. This is not due to repulsion between the molecules, but to their motions. Gases move into a good vacuum much more quickly than they diffuse through one another. In diffusion their motion is frequently arrested by molecular collisions, and hence diffusion is impeded.

The property of rapid expansion into a free space is

a highly important one. Witness the operation of a gasoline engine, in which the inlet valve presents only a narrow opening for a small fraction of a second; and yet this brief period suffices for the explosive mixture to enter and fill the cylinder.

24. Pressure Produced by Molecular Bombardment. — It would be possible to keep an iron plate suspended horizontally in the air by the impact of a great many bullets fired up against its under surface. The clatter of an indefinitely large number of hailstones on a roof forms a continuous sound, and their fall beats down a field of grain flat to the ground. So the rapidly moving molecules of a gas strike innumerable minute blows against the walls of the containing vessel and these blows compose a continuous pressure. This, in brief, is the kinetic theory of the pressure of a gas.

25. The Velocity of Molecules. — It has been found possible to calculate the velocity which the molecules of air must have under standard conditions to produce by their impact against the walls of a vessel the pressure of one atmosphere, or 1033 gm. per square centimeter. It is about 450 m. per second. For the same pressure of hydrogen, which is only one fourteenth as heavy as air, the velocity has the enormous value of 1850 m. per second. The high speed of the hydrogen molecules accounts for their relatively rapid progress through porous walls.

26. Diffusion of Liquids. — Liquids diffuse into one another in a manner similar to that of gases, but the process is indefinitely slower. Diffusion in liquids, as in gases, shows that the molecules have independent motion because they move more or less freely among one another.

Let a tall jar be nearly filled with water colored with blue litmus, and let a little strong sulphuric acid be introduced into the jar at the bottom by means of a thistle tube (Fig. 12). The density of the acid is 1.8 times that of the litmus solution, and the acid therefore remains at the bottom with a well-defined surface of separation, which turns red on the litmus side because acid reddens litmus. But if the jar be left undisturbed for a few hours, the line of separation will lose its sharpness and the red color will move gradually upward, showing that the acid molecules have made their way toward the top.

Fig. 12

27. Diffusion of Solids. — The diffusion of solids is much less pronounced than the diffusion of gases and liquids, but it is known to occur. Thus, if gold be overlaid with lead, the presence of gold throughout the lead may in time be detected. Mercury appears to diffuse through lead at ordinary temperatures; in electroplating the deposited metal diffuses slightly into the baser metal; at higher temperatures metals diffuse into one another to a marked degree, so that there is evidence of molecular motion in solids also.

II. SURFACE PHENOMENA

28. Molecular Forces in Liquids. — A primitive idea of force is derived from the sense of muscular exertion in lifting a weight, pushing a cart, stretching a spring, catching a ball, throwing a stone, or making intense muscular effort in running at top speed. By an easy transition of ideas we carry this conception over to forces other than those exerted by men and animals, such as those between the molecules of a body. *Molecular forces* act only through insensible distances, such as the distances separating the molecules of solids and liquids. A clean glass rod does not attract water until there is actual contact between the

two. If the rod touches the water, the latter clings to the glass, and when the rod is withdrawn, a drop adheres to it. If the drop is large enough, its weight tears it away, and it falls as a little sphere.

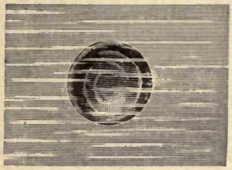


Fig. 13

By means of a pipette a large globule of olive oil may be introduced below the surface of a mixture of water and alcohol, the mixture having been adjusted to the same density as that of the oil by varying the proportions. The globule then assumes a truly *spherical form* and floats anywhere in the mixture (Fig. 13).

Cover a smooth board with fine dust, such as lycopodium powder or powdered charcoal. If a little water be dropped upon it from a height of about two feet, it will scatter and take the form of little spheres (Fig. 14).

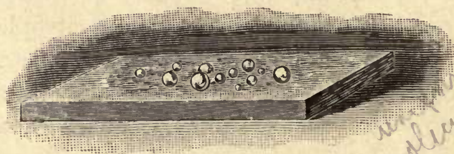


Fig. 14

In all these illustrations the spherical form is accounted for by the forces between the molecules of the liquid. They produce uniform molecular pressure and form little spheres, because a spherical surface is the smallest that will inclose the given volume.

29. Condition at the Surface of a Liquid. — Bubbles of gas released in the interior of a cold liquid and rising to the surface often show some difficulty in breaking through. A sewing needle carefully placed on the surface of water floats. The water around the needle is depressed and the needle rests in a little hollow (Fig. 15).

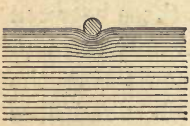


Fig. 15

Let two bits of wood float on water a few

millimeters apart. If a drop of alcohol is let fall on the water between them, they suddenly fly apart.

A thin film of water may be spread evenly over a chemically clean glass plate; but if the film is touched with a drop of alcohol on a thin glass rod, the film will break, the water retiring and leaving a dry area around the alcohol.

The sewing needle indents the surface of the water as if the surface were a tense membrane or skin, and tough enough to support the needle. This surface skin is weaker in alcohol than in water; hence the bits of wood are pulled apart and the water is withdrawn from the spot weakened with alcohol.

30. Surface Tension. — The molecules composing the surface of a liquid are not under the same conditions of equilibrium as those within the liquid. The latter are attracted equally in all directions by the surrounding molecules, while those at the surface are attracted downward and laterally, but not upward (Fig. 16). The result is an unbalanced molecular force toward the interior of the liquid, so that the surface layer is compressed and tends to contract. The contraction means that the surface acts like a stretched membrane, which molds the liquid into as small a volume as possible. Liquids in small masses, therefore, always tend to become spherical.

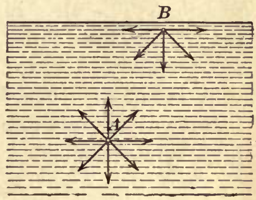


Fig. 16

31. Illustrations. — Tears, dewdrops, and drops of rain are spherical because of the tension in the surface film. Surface tension rounds the end of a glass rod or stick of sealing wax when softened in a flame. It breaks up a small stream of molten lead into little sections, and molds them into spheres which cool as they fall and form shot. Small globules of mercury on a clean glass plate are slightly flattened by their weight, but the smaller the globules the more nearly spherical they are.

Make a stout ring three or four inches in diameter with a handle (Fig. 17). Tie to it a loop of soft thread so that the loop may hang near the middle of the ring. Dip the ring into a soap solution containing glycerine, and get a plane film. The thread will float in it. Break the film inside the loop with a warm pointed wire, and the loop will spring out into a circle. The tension of the film attached to the thread pulls it out equally in all directions.

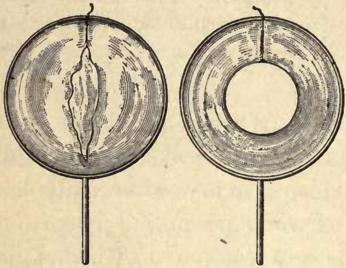


Fig. 17

Interesting surfaces may be obtained by dipping skeleton frames made of stout wire into a soap solution. The films in Fig. 18 are all plane, and the angles where three surfaces meet along a line are necessarily 120° for equilibrium.

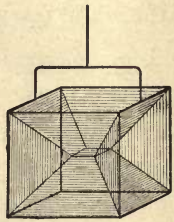


Fig. 18

A bit of gum camphor on warm water, quite free from an oily film, will spin around in a most erratic manner. The camphor dissolves unequally at different points, and thus produces unequal weakening of the surface tension in different directions.

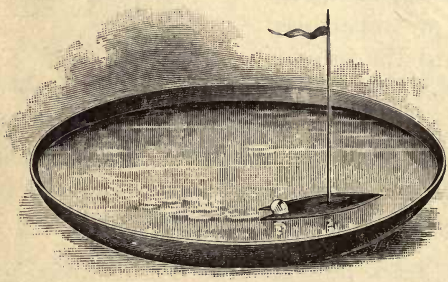


Fig. 19

Make a tiny wooden boat and cut a notch in the stern; in this notch put a piece of camphor gum (Fig. 19). The camphor will weaken the tension astern, while the tension at the bow will draw the boat forward.

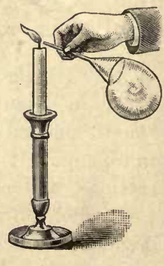


Fig. 20

Surface tension makes a soap bubble contract. Blow a bubble on a small funnel and hold the open tube near a candle flame (Fig. 20). The ex-

pelled air will blow the flame aside, and the smaller the bubble the more energetically will it expel the air.

A small cylinder of fine wire gauze with solid ends, if completely immersed in water and partly filled, may be lifted out horizontally and hold the water. A film fills the meshes of the gauze and makes the cylinder air-tight; if it is broken by blowing sharply on it, the water will quickly run out.

32. Capillary Elevation and Depression. — If a fine glass tube, commonly called a capillary or hairlike tube, is partly immersed vertically in water, the water will rise higher in the tube than the level outside; on the other hand, mercury is depressed below the level outside. The top of the little column of water is concave, while that of the column of mercury is convex upward (Fig. 21).

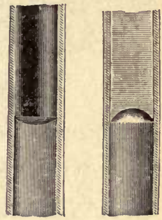


Fig. 21

Familiar examples of capillary action are numerous. Blotting paper absorbs ink in its fine pores, and oil rises in a wick by capillary action. A sponge absorbs water for the same reason; so also does a lump of sugar. A cotton or a hemp rope absorbs water, increases in diameter, and shortens. A liquid may be carried over the top of a vessel by capillary action in a large loose cord, like water in a siphon. Many salt solutions construct their own capillary highway up over the top of the open glass vessel in which they stand. They first rise by capillary action along the surface of the glass, then the water evaporates, leaving the salt in fine crystals, through which the solution rises by capillary action still higher. This process may continue until the liquid flows over the top and down the outside of the vessel.

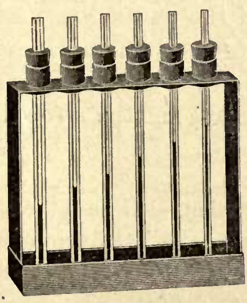


Fig. 22

33. Laws of Capillary Action. — Support vertically several clean glass tubes of small internal diameter in a vessel of pure water (Fig. 22). The water will rise in these tubes, highest in the one of small-

est diameter, and least in the one of greatest. With mercury in place of water, the depression will be the greatest in the smallest tube.

If two chemically clean glass plates, inclined at a very small angle, be supported with their lower edges in water, the height to which the water will rise at different points will be inversely as the distance between the plates, and the water line will be curved as in Fig. 23.

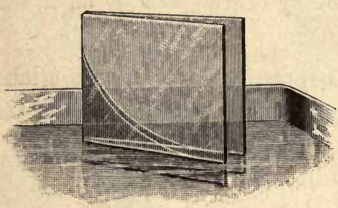


Fig. 23

These experiments illustrate the following laws:

I. *Liquids ascend in tubes when they wet them, that is, when the surface is concave; and they are depressed when they do not wet them, that is, when the surface is convex.*

II. *For tubes of small diameter, the elevation or depression is inversely as the diameter of the tube.*

34. Capillary Action in Soils. — The distribution of moisture in the soil is greatly affected by capillarity. Water spreads through compact porous soil as tea spreads through a lump of loaf sugar. As the moisture evaporates at the surface, more of it rises by capillary action from the supply below. To conserve the moisture in dry weather and in "dry farming," the surface of the soil is loosened by cultivation, so that the interstices may be too large for free capillary action. The moisture then remains at a lower level, where it is needed for the growth of plants.

35. Capillarity related to Surface Tension. — The attraction of glass for water is greater than the attraction of water for itself (§ 10). When a liquid is thus attracted by a solid, the liquid wets it and rises with a concave

surface upward (Fig. 24). The surface tension in a curved film makes the film contract and produces a pressure towards its center of curvature, as shown in the case of the soap bubble (§ 31). When the surface of the liquid in the tube is concave, the resultant of this normal pressure is a force upward; the downward pressure of the liquid under the film is thus reduced, and the liquid rises until the weight of the column *AE* downward just equals the resultant of the normal forces of the film upward. When the liquid does not wet the tube, the normal pressure of the film is downward, and the column sinks until the downward pressure is counterbalanced by the upward pressure of the liquid outside.

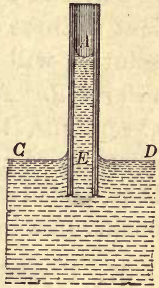


Fig. 24

III. MOLECULAR FORCES IN SOLIDS

36. Solution of Solids. — The solution of certain solids in liquids has become familiar by the use of salt and sugar in liquid foods. The solubility of solids is limited, for it depends on the nature of both the solid and the solvent, — the liquid in which it dissolves. At room temperatures, table salt dissolves about three times as freely in water as in alcohol; while grease, which is practically insoluble in water, dissolves readily in benzine or gasoline.

Solution in a small degree takes place in many unsuspected cases. Thus, certain kinds of glass dissolve to an appreciable extent in hot water. Many rocks are slightly soluble in water, and the familiar adage that the "constant dropping of water wears away a stone" is accounted for, in part at least, by the solution of the stone. Flint glass, out of which cut glass vessels are made, dissolves to some extent in aqua ammonia; this liquid should not be kept in cut glass bottles, nor should cut glass be washed in water containing ammonia.

There is a definite limit to the quantity of a solid which will dissolve at any temperature in a given volume of a liquid. For example, 360 gm. of table salt will dissolve in a liter of water at ordinary temperatures; this is equivalent to three quarters of a pound to the quart. When the solution will dissolve no more of the solid, it is said to be *saturated*. As a general rule, though it is not without exceptions, the higher the temperature, the larger the quantity of a solid dissolved by a liquid. A liquid which is saturated at a higher temperature is *supersaturated* when cooled to a lower one.

37. Crystallization. — When a saturated solution evaporates, the liquid only passes off as a vapor; the dissolved substance remains behind as a solid. When the solid thus separates slowly from the liquid and the solution remains undisturbed, the conditions are favorable for the molecules to unite under the influence of their mutual attractions, and they assume regular geometric forms called *crystals*. Similar conditions exist when a saturated solution cools and becomes supersaturated. The presence of a minute crystal of the solid then insures the formation of more. The process of the separation of a solid in the form of crystals is known as *crystallization*.

Dissolve 100 gm. of common alum in a liter of hot water. Hang some strings in the solution and set aside in a quiet place for several hours. The strings will be covered with beautiful transparent octahedral crystals. Copper sulphate may be used in place of the alum; large blue crystals will then collect on the strings.

Filter a saturated solution of common salt and set aside for twenty-four hours. An examination of the surface will reveal groups of crystals floating about. Each one of these, when viewed through a magnifying glass, will be found to be a little cube.

Ice is a compact mass of crystals, and snow consists of crystals

formed from the vapor of water. They are of various forms, but all hexagonal in outline (Fig. 25).[1]

38. Molecular Strength. — To tear apart a solid, a stretching force must be applied in excess of the forces holding together the molecules on opposite sides of the

Fig. 25

fracture. Tenacity (§ 12) is accounted for by this force of cohesion and is a measure of it.

Steel has the greatest tensile strength of all metals; a steel rod 1 sq. in. in cross section requires a stretching force of about 65 tons to break it. For the same cross section, hard drawn copper breaks under a tension of from 23 to 34 tons. The breaking tension varies as the cross section.

39. Molecular Equilibrium. — When a semiliquid solid, such as glass at a high temperature, is suddenly chilled, the molecules do not have time to arrange themselves under the cohesive forces acting on them, and the molecular grouping is one of more or less unstable restraint.

Fig. 26

Prince Rupert drops (Fig. 26) are made by dropping melted glass into cold water. The outside is suddenly chilled and solidified, while the interior is still fused, and when it cools it must accommodate itself to the dimensions of the outer skin.

[1] These figures were made from microphotographs taken by Mr. W. A. Bentley, Jericho, Vt.

The drop is thus under great tension. With a pair of pliers break off the tip of the drop under water in a tumbler, or scratch with a file; the whole drop will fly to powder with almost explosive violence.

A large tall jar on foot is usually thick at the bottom, and has been imperfectly annealed. Such jars have not infrequently been broken by a scratch inside, made, for example, by stirring emery powder in water by means of a long wooden stick. A scratch inside is usually fatal to a lamp chimney.

40. Elasticity. — Apply pressure to a tennis ball, stretch a rubber band, bend a piece of watch spring, twist a strip of whalebone. In each case the form or the volume has been changed, and the body has been *strained.* A *strain* means either a change of size or a change of shape. As soon as the distorting force, or *stress*, has been withdrawn, these bodies recover their initial volume and dimensions. *This property of recovery from a strain when the stress is removed is called elasticity.* It is called *elasticity of form* when a body recovers its form after distortion; and *elasticity of volume* when the temporary distortion is one of volume. Gases and liquids have perfect elasticity of volume, because they recover their former volume when the original pressure is restored. They have no elasticity of form. Some solids, such as shoemaker's wax, putty, and dough, when long-continued force is applied, yield slowly and never recover.

The elasticity of a body may be called forth by pressure, by stretching, by bending, or by twisting. The bounding ball and the popgun are illustrations of the first; rubber bands are familiar examples of the second; bows and springs of the third; and the stretched spiral spring exemplifies the fourth.

41. Hooke's Law. — Solids have a limit to their distortion, called the *elastic limit*, beyond which they yield and are incapable of recovering their form or volume. The

elastic limit of steel is very high; steel breaks before there is much permanent distortion. On the other hand, lead does not recover completely from any distortion.

When the strain in an elastic body does not exceed the elastic limit, in general *the distortion is proportional to the distorting force.* This relation is known as *Hooke's law.*

Clamp a meter stick to a suitable support (Fig. 27), and load the free end with some convenient weight in a light scale pan; observe the bending of the stick by means of the vertical scale and the pointer. Then double the weight and note the new deflection. It should be double the first. The amount of bending or distortion of the bar is proportional to the weight.

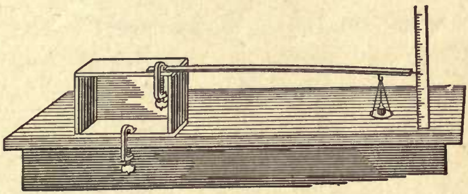


Fig. 27

Generally, *for all elastic displacements within the elastic limit, the distortions of any kind, due to bending, stretching, or twisting, are proportional to the forces producing them.*

Questions and Problems

1. When a glass tube is cut off its edges are sharp; why do they become rounded by softening in a blowpipe flame?

2. Why does a small vertical stream of water break into drops?

3. Why can you not write with ink on blotting paper?

4. Explain the action of blotting paper; of a towel in drying the wet hands; of a sponge.

5. A soap bubble is filled with air. Is the air inside denser or rarer than the air outside?

6. If dry wooden wedges are driven into holes or a channel in a stone, and are then wet with water, what is the effect?

7. Why does an automobile ride easier with pneumatic tires than with solid rubber ones?

8. Are the divisions on the scale of a spring balance equal? What law is illustrated?

9. If an iron wire one tenth inch in diameter will safely support 300 pounds, how many pounds will one support one fifth inch in diameter?

10. If a steel rod 10 ft. long is stretched within its elastic limit 0.15 in. by a certain weight, how much would a rod 20 ft. long be lengthened by the same weight? By half the weight?

CHAPTER III

MECHANICS OF FLUIDS

I. PRESSURE OF FLUIDS

42. Characteristics of Fluids. — A fluid has no shape of its own, but takes the shape of the containing vessel. It cannot resist a stress unless it is supported on all sides. The molecules of a fluid at rest are displaced by the slightest force; that is, a fluid yields to the continued application of a force tending to change its shape. But fluids exhibit wide differences in *mobility*, or readiness in yielding to a stress. Alcohol, gasoline, and sulphuric ether are examples of very mobile liquids; glycerine is very much less mobile, and tar still less so. In fact, liquids shade off gradually into solids. A stick of sealing wax supported at its ends yields continuously to its own weight; in warm weather paraffin candles do not maintain an upright position in a candlestick, but curve over or bend double; a cake of shoemaker's wax on water, with bullets on it and corks under it, yields to both and is traversed by both in opposite directions. It will even flow very slowly down a tortuous channel. At the same time, sealing wax and shoemaker's wax when cold break readily under the blow of a hammer.

43. Viscosity. — *The resistance of a fluid to flowing under stress is called viscosity.* It is due to molecular friction. The slowness with which a fine precipitate, thrown down by chemical action, settles in water is owing to the vis-

cosity of the liquid; and the slow descent of a cloud is accounted for by the viscosity of the air. Viscosity varies between wide limits. It is less in gases than in liquids; hot water is less viscous than cold water; hence the relative ease with which a hot solution filters.

44. Liquids and Gases. — Fluids are divided into liquids and gases. *Liquids*, such as water and mercury, are but slightly compressible, while *gases*, such as air and hydrogen, are highly compressible. A *liquid* offers great resistance to forces tending to diminish its volume, while a *gas* offers relatively small resistance. Water is reduced only 0.00005 of its volume by a pressure equal to that of the atmosphere (practically 15 lb. to the square inch), while air is reduced to one half its volume by the same additional pressure.

Then, too, *gases* are distinguished from liquids by the fact that any mass of gas when introduced into a closed vessel always completely fills it, whatever its volume. A liquid has a bulk of its own, but a gas has not, since a gas expands indefinitely as the pressure on it decreases.

45. Pascal's Principle. — A solid transmits pressure only in the direction in which the force acts; but a fluid transmits pressure in every direction. Hence the law:

Pressure applied to an inclosed fluid is transmitted equally in all directions and without diminution to every part of the fluid and of the interior of the containing vessel.

This is the fundamental law of the mechanics of fluids. It is a direct consequence of their mobility, and it applies to both liquids and gases. It was first announced by Pascal in 1653.

Galileo Galilei (1566–1642) was born at Pisa, Italy. He was a man of great genius, and an experimental philosopher of the first rank. He was educated as a physician, but devoted his life to mathematics and physics. He discovered the properties of the pendulum, invented the telescope bearing his name, and was ardent in his support of the doctrine that the earth revolves around the sun. Besides his original work in physics, he made interesting discoveries in astronomy.

Blaise Pascal (1623–1662) was born at Clermont in Auvergne. He was both a mathematician and a physicist. Even as a youth he showed remarkable learning, and at the age of seventeen achieved renown with a treatise on conic sections. He is best known for his announcement in 1658 of the important law of fluid pressure bearing his name. He distinguished himself by his researches in conic sections, in the properties of the cycloid, and the pressure of the atmosphere.

ILLUSTRATIONS. — Fit a perforated stopper to an ounce bottle, preferably with flat sides, and mounted in a suitable frame (Fig. 28). Fill the bottle with water and then force a metal plunger through the hole in the stopper. If the plunger fits the stopper water-tight, the pressure applied to the plunger will be transmitted to the water as a bursting pressure; and the whole pressure transmitted to the inner surface of the bottle will be as much greater than the pressure applied as the area of this surface is greater than that of the end of the plunger.

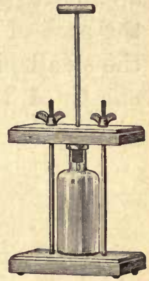


Fig. 28

Figure 29 is a form of syringe made of glass; the hollow sphere at the end has several small openings. Fill with water and apply pressure to the piston. The water will escape in a series of jets of apparently equal velocities, although only one of them is directly in line with the piston.

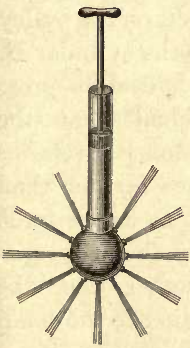


Fig. 29

Fit a glass tube to the stem of a small rubber balloon; blow into the tube; the balloon will expand equally in all directions, forming a sphere and showing equal pressures in all directions. A large soap bubble shows the same thing.

46. The Hydraulic Press. — An important application of Pascal's principle is the *hydraulic press*. Figure 30 is a section showing the principal parts. A heavy piston P works water-tight in the larger cylinder A, while in the smaller one the piston p is moved up and down as a force pump; it pumps water or oil from the reservoir D and forces it through the tube C into the cylinder A. When the piston p of the pump is forced down, the

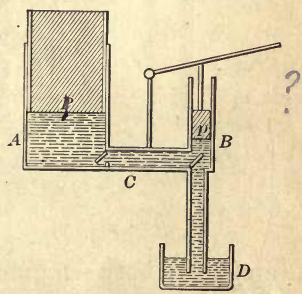


Fig. 30

liquid transmits the pressure to the base of the larger piston, on which the force R is as many times the force E applied to p as the area of the large piston is greater than the area of the small one. If the cross sectional area of the small piston is represented by a, and that of the large one by A, the ratio between the forces acting on the two pistons is

$$\frac{R}{E} = \frac{A}{a} = \frac{D^2}{d^2},$$

where D and d are the diameters of the large and small pistons respectively.

Figure 31 illustrates a press driven by a belt on the pulley P. F and F are pumps forcing water into the cylinder B.

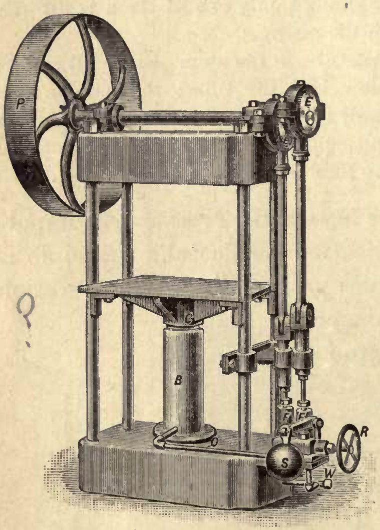


Fig. 31

In the hydraulic press it is evident that the small piston travels as many times farther than the large one as the force exerted by the large piston is greater than the effort applied to the small one.

47. The Hydraulic Elevator. — A modern application of Pascal's principle is the hydraulic elevator. A simple form is shown in Fig. 32. A long piston P carries the cage A, which runs up and down between guides and is partly counterbalanced by a weight W. The piston runs in a tube or pit sunk to a

depth equal to the height to which the cage is designed to rise. Water under pressure enters the pit from the pipe *m* through the valve *v*. Turned in one direction the valve admits water to the sunken cylinder, and the pressure forces the piston up; turned in the other direction it allows the water to escape into the sewer, and the elevator descends by its own weight.

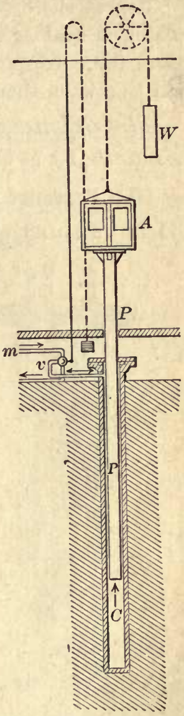


Fig. 32

When greater speed is required, the cage is connected to the piston indirectly by a system of pulleys. The cage then usually runs four times as fast as the piston.

48. Downward Pressure of a Liquid. — The weight of each layer of a liquid is transmitted to every layer at a lower level.

A glass cylinder is cemented into a metal ferule which screws into a second short cylinder, across the base of which is tied a disk of sheet rubber. The pointer below acts as a lever, the short arm pressing against the center of the rubber disk, and the long arm moving over a scale (Fig. 33). It should be adjusted to point to zero to begin with. Fill the glass cylinder one third full of water and note the reading of the pointer on the scale. Add water until the cylinder is two thirds full; the reading of the pointer will be doubled. Finally fill the cylinder, and the reading on the scale should be three times the first one. Hence,

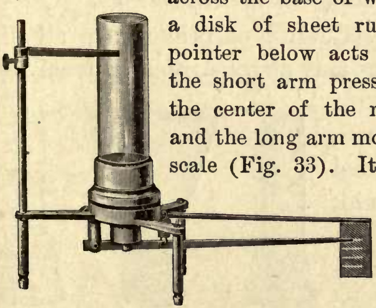


Fig. 33

The downward pressure of a liquid is proportional to the depth.

Repeat the experiment with a saturated solution of common salt, which is heavier than water. Every pointer reading will be greater than the corresponding ones with water, but the same relation will exist between them. Hence,

The downward pressure of a liquid is proportional to its density (§ 59).

49. Pressure at a Point. — The three glass tubes of Fig. 34 have short arms of the same length, measured from the bend to the mouth. They open in different directions, — upward, downward, and sidewise. Place mercury to the same depth in all the tubes, and lower them into a tall jar filled with water. When the open ends of the short arms are kept at the same level, the change in the level of the mercury is the same in all of them. Hence,

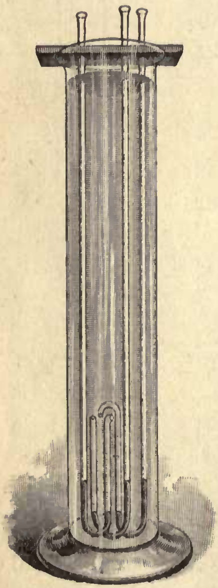


Fig. 34

The pressure at a point in a liquid is the same in all directions.

The equality of pressure in all directions may also be inferred from the absence of currents in a vessel of liquid, since an unbalanced pressure would produce motion of the liquid.


Fig. 35

50. Pressure Independent of the Shape of the Vessel. — Proceeding as in § 48, use in succession the three vessels

shown in Fig. 35. They have equal bases, but differ in shape and volume. They are known as Pascal's vases. Fill each in succession to the same height, and note the reading of the pointer. It will be the same for all, notwithstanding the great difference in the amount of water. Hence,

The downward pressure in a liquid is independent of the shape of the vessel.

The apparent contradiction of unequal masses of a liquid producing equal pressures is known as the *hydrostatic paradox.* It is only another form of Pascal's principle.

51. Total Pressure on Any Surface. — *The total pressure of a liquid on any horizontal surface is equal to the weight of a column of the liquid whose base is the area pressed upon, and whose height is the depth of this area below the surface of the liquid.*

Let A denote the area pressed upon, H its depth, and d the weight of a unit volume of the liquid. Then the whole pressure on this area is

$$P = AHd. \quad . \quad . \quad . \text{ (Equation 1)}$$

The pressure on any immersed surface of any inclination or shape is found by computing the pressures on all the elementary areas into which the surface may be divided and adding them together. The result is expressed as follows:

The total pressure on any immersed surface is equal to the weight of a column of the liquid whose base has an area equal to that of the surface pressed upon, and whose height is equal to the depth of the center of gravity of this surface below the surface of the liquid.

Formula (1) applies to both cases. In the English sys-

tem d for water is 62.4 lb. per cubic foot; in the metric system it is 1 gm. per cubic centimeter.

EXAMPLE. The upstream face of a dam measures 20 ft. from top to bottom, but it slopes so that its center of figure is only 7 ft. from the surface of the water when the dam is full. Find the perpendicular pressure against the dam for every foot of length.

SOLUTION. The area of the face of the dam per foot in length is 20 sq. ft. Hence the weight of the column of water to represent the pressure is $20 \times 7 \times 62.4 = 8736$ lb.

52. Surface of a Liquid at Rest. — The free surface of a liquid under the influence of gravity alone is horizontal. Even viscous liquids assume a horizontal surface in course of time. The sea, or any other large expanse of water, is a part of the spheroidal surface of the earth. When one looks with a field glass at a long straight stretch of the Suez Canal, the water and the retaining wall as contrasting bodies appear distinctly curved as a portion of the rounded surface of the earth.

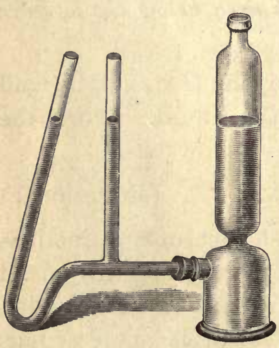


Fig. 36

53. Level of Liquid in Connected Vessels. — The water in the apparatus of Fig. 36 rises to the same level in all the branches. There is equilibrium because the pressures on opposite sides of any cross section of the liquid in the connecting tube are equal, since they are due to liquid columns of the same height.

The glass *water gauge*, used to show the height of the water in a steam boiler, is an application of this principle; also the *water level*, consisting of two glass tubes, joined by a long rubber tube, and employed by builders for leveling foundations.

Artesian or *flowing wells* illustrate on a grand scale the tendency of

water "to seek its level." In geology an artesian basin is one composed of superposed strata of great extent, one of which is permeable to water, and lies between two of clay or other material through which water does not percolate (Fig. 37). This stratum crops out at some

Fig. 37

higher level where water finds entrance, as at *A*. When a well is bored through the overlying strata in the valley, water issues on account of the pressure transmitted from higher points at a distance. There are 8000 or 10,000 artesian wells in the western part of the United States; some notable ones are at Chicago, St. Louis, New Orleans, Charleston, and Denver. In Europe there are very deep flowing wells in Paris (2360 ft.), Berlin (4194 ft.), and near Leipzig (5740 ft).

Questions and Problems

1. Why do gas bubbles rising through water from a marshy bottom grow larger as they ascend?

2. Why is the water pressure greater in the basement of a house than on the top floor?

3. A force of 150 lb. is applied to a small piston of an hydraulic press; the two pistons have diameters of 1 in. and 5 in. respectively; what pressure is exerted on the larger one?

4. A swimming tank 50 ft. square is filled with water to a depth of 10 ft. What is the total pressure on the bottom? On one side?

5. A glass cylinder 76 cm. high is level full of mercury. What is the pressure in grams per square centimeter on the bottom? (1 $cm.^3$ of mercury weighs 13.6 gm.)

6. A recording pressure gauge registered zero at the surface of a fresh-water lake and 150 lb. per square inch at the bottom. Calculate the depth of the lake.

7. How high would water rise in the pipes of a building if a pressure gauge shows that the pressure at the ground floor is 40 lb. per square inch.?

8. A cylindrical steel tank has an internal diameter of 20 ft. and a height of 25 ft. When it is filled with kerosene, weight 56 lb. per cubic foot, what is the total pressure on the bottom? On the cylindrical side?

9. An hydraulic lift carries an unbalanced weight of 3000 lb. If the piston supporting the lift is 8 in. in diameter, what pressure of water per square inch will be necessary?

10. A vertical tube is filled with mercury, weighing 13.6 gm. per cubic centimeter, to a depth of 3 m. What is the pressure in grams per square centimeter on the bottom?

11. What is the pressure per square foot at a depth of 2 mi. in the ocean, sea water weighing 64 lb. per cubic foot?

12. A diver is working at a depth of 30 ft. What is the pressure per square inch on the surface of his body? In fresh water? In the ocean?

13. A hole in the bottom of a ship 25 ft. below the surface of the water is covered with canvas. What is the pressure per square inch against the canvas?

14. An oak cask 2 ft. high stands on end and into its head is screwed a vertical iron pipe an inch in diameter and 29 ft. high. The cask and the pipe are both filled with water to the top. The cask has a bunghole midway between its ends and 2 in. in diameter. What is the total pressure on the bung?

II. BODIES IMMERSED IN LIQUIDS

54. Buoyancy. — A fresh egg sinks in fresh water and floats in brine; a marble sinks in water and floats in mercury; a piece of oak floats in water, but a piece of the dense wood known as "lignum vitæ" sinks. When a bather wades up to his neck in the sea, he is nearly lifted off his feet by the buoyant force of the water. These facts show that the resultant pressure of a liquid on a body immersed in it is a vertical force upward, and that it counterbalances a part or the whole of a body's weight. *The resultant upward pressure of a liquid on a body immersed in it is called buoyancy.*

55. Archimedes' Principle. — Archimedes discovered the law of buoyancy about 240 B.C. while attempting to determine the composition of the golden crown of Hiero II, King of Syracuse, who suspected that the goldsmith had mixed base metal with the gold. The law is:

A body immersed in a liquid is buoyed up by a force equal to the weight of the liquid displaced by it.

If a cube be immersed in water (Fig. 38), the pressures on the vertical sides *a* and *b* are equal and in opposite directions. The same is true of the other pair of vertical faces. There is therefore no resultant horizontal pressure. On *d* there is a downward pressure equal to the weight of the column of water having the face *d* as a base, and the height *dn*. On *c* there is an upward pressure equal to the weight of a column of water whose base is the area of *c*, and whose height is *cn*. The upward pressure therefore exceeds the downward pressure by the weight of the prism of water whose base is the face *c* of the cube, and whose height is the difference between *cn* and *dn*, or *cd*. This is the weight of the liquid displaced by the cube.

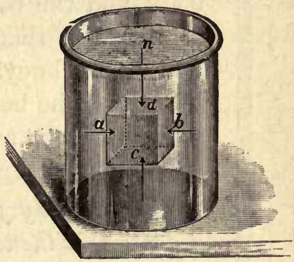


Fig. 38

Fig. 39

A metallic cylinder 5.1 cm. long, and 2.5 cm. in diameter has a volume of almost exactly 25 cm.^{3}. Suspend it by a fine thread from one arm of a balance (Fig. 39) and counterpoise. Then submerge it in water as in the figure. The equilibrium will be restored by placing 25 gm. in the pan above the cylinder. The cylinder displaces 25 cm.^{3} of water

weighing 25 gm., and its apparent loss of weight is 25 gm. The temperature of the water should be down near freezing.

56. Equilibrium of Floating Bodies. — If a body be immersed in a fluid, it may displace a weight of the fluid *less* than, *equal* to, or *greater* than its own weight. In the first case, the upward pressure is less than the weight of the body and the body sinks. In the second case, the upward pressure is equal to the weight of the body and the body is in equilibrium. In the third case, the upward pressure exceeds the weight of the body, and the body rises until enough of it is out of water so that these forces become equal. In liquids the buoyancy is independent of the depth so long as the body is wholly immersed, but it decreases as soon as the body begins to emerge from the liquid. Hence,

When a body floats on a liquid it sinks to such a depth that the weight of the liquid displaced equals its own weight.

Fig. 40

Make a wooden bar 20 cm. long and 1 cm. square (Fig. 40). Drill a hole in one end and fill with enough shot to give the bar a vertical position when floating with nearly its whole length in water. Graduate the bar in millimeters along one edge, beginning at the weighted end, and coat with hot paraffin. Weigh the bar and float it in water, noting the volume in cubic centimeters immersed. This volume is equal to the volume of water displaced; and since 1 cm.^{3} of water weighs 1 gm., the weight of the water displaced should equal the volume of the bar immersed. This will be found also very nearly equal to the weight of the loaded bar.

57. Center of Buoyancy. — *The center of buoyancy is the center of volume of the displaced liquid.* Two forces act on every floating body, its *weight*, which is a force acting downward with its point of application at the center of

gravity (§ 118) of the body, and *buoyancy*, a force acting vertically upward, and with its point of application at the center of buoyancy. If these two forces are not in the same vertical line (Fig. 41, *D*), the effect is to rotate the floating body. If the vertical line through the center of buoyancy cuts the vertical through both centers in the position of equilibrium *A* at a point *above the center of gravity G* (as in *D*), the action is to right the body, and it has *angular stability*. The object of ballast in a ship is to lower the center of gravity, and to increase its angular stability.

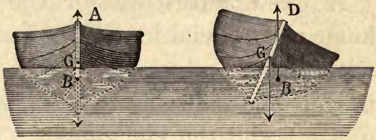


Fig. 41

58. The Cartesian Diver. — Descartes, a French scientist, illustrated the principle of Archimedes by means of an hydrostatic toy, since called the *Cartesian diver*. It is made of glass, is hollow, and has a small opening near the bottom. The figure is partly filled with water so that it just floats in a jar of water (Fig. 42). When pressure is applied to the sheet rubber tied over the top of the jar, it is transmitted to the water, more water enters the floating figure, and the air is compressed. The figure then displaces less water and sinks. When the pressure is relieved, the air in the diver expands and forces water out again. The actual displacement of water is then increased, and the figure rises to the surface. The water in the diver may be so nicely adjusted that the little figure will sink in cold water, but will rise again when the water


Fig. 42

has reached the temperature of the room, and the air in the figure has expanded.

A good substitute for the diver is a small inverted homeopathic vial in a flat 16-oz. prescription bottle, filled with water and closed with a rubber stopper. By pressing on the sides of the bottle, it yields, the air is compressed, and the vial sinks.

A submarine boat is a modern Cartesian diver on a large scale. It is provided with tight compartments, into which water may be admitted to make it sink. It may be made to rise to the surface by expelling some of the water by means of strong pumps.

III. DENSITY AND SPECIFIC GRAVITY

59. Density. — *The density of a substance is the number of units of mass of it contained in a unit of volume.* In the *c. g. s.* system it is the number of grams per cubic centimeter. For example, if 4 cm.^{3} of a substance contain a mass of 10 gm., its density is 2.5 gm. per cubic centimeter. In the English system density is the number of pounds per cubic foot, or ounces per cubic inch. By definition

$$density = \frac{mass}{volume},$$

or in symbols,

$$d = \frac{m}{v}; \text{ whence } v = \frac{m}{d} \text{ and } m = vd. \quad \text{(Equation 2).}$$

60. Density of Solids. — The density of a solid body is its mass divided by its volume. Its mass may always be obtained by weighing, but the volume of an irregular solid cannot be obtained from a measurement of its dimensions. In the *c. g. s.* system, however, the principle of Archimedes furnishes a simple method of finding the

volume of a solid, however irregular it may be; for the volume of an immersed solid is numerically equal to its loss of weight in water (§ 55).

Then $$density = \frac{mass}{loss\ of\ weight\ in\ water}.$$

Consider two cases:

A. *Solids heavier than water.* — Find the mass of the body in air in terms of grams; if it is insoluble in water, find its apparent loss of weight by suspending it in water (Fig. 43). This loss of weight is equal to the weight of the volume of water displaced by the solid (§ 55). But the volume of a body in cubic centimeters is the same as the mass in grams of an equal volume of water. The mass divided by this volume is the density.

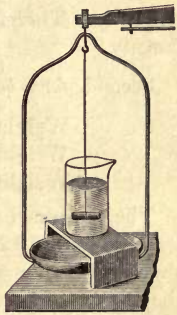


Fig. 43

B. *Solids lighter than water.* — If the body floats, its volume may still be obtained by tying to it a sinker heavy enough to force it beneath the surface. Let w_1 denote the weight in grams required to counterbalance when the body is in the air, and the attached sinker in the water; and let w_2 denote the weight to counterbalance when both body and sinker are under water (Fig. 44). Then obviously $w_1 - w_2$ is equal to the upward pressure on the body alone, and is therefore numerically equal to the volume of the body (§ 55). The mass divided by this volume is the density.

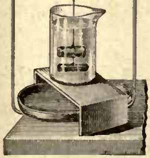


Fig. 44

If the solid is soluble in water, a liquid of known density, in which the body is not soluble, must be used in place of water.

The buoyancy of this liquid, divided by the density of the liquid, gives as before the volume of the solid; its density is then found as before.

Examples. — First, *for a body heavier than water.*

Weight of body in air	10.5 gm.
Weight of body in water	6.3 gm.
Weight of water displaced	4.2 gm.

Since the density of water is 1 gm. per cubic centimeter, the volume of the water displaced is 4.2 cm.^{3}. This is also the volume of the body. Therefore, $10.5 \div 4.2 = 2.5$ gm. per cubic centimeter is the density.

Second, *for a body lighter than water.*

Weight of body in air	4.8 gm.
Weight of sinker in water	10.2 gm.
Weight of body and sinker in water	8.4 gm.

The combined weight of the body in air and the sinker in water is, then, $4.8 + 10.2 = 15$ gm. But when the body is attached to the sinker, their apparent combined weight is only 8.4 gm. Therefore the buoyant effort on the body is $15 - 8.4 = 6.6$ gm., and this is the weight of the water displaced by the body, and hence its volume is 6.6 cm.^{3}. The density is, then, $4.8 \div 6.6 = 0.73$ gm. per cubic centimeter.

Third, *for a body soluble in water.* Suppose it is insoluble in alcohol, the density of which is 0.8 gm. per cubic centimeter.

Weight of body in air	4.8 gm.
Weight of body in alcohol	3.2 gm.
Weight of alcohol displaced	1.6 gm.

The volume of alcohol displaced is $1.6 \div 0.8 = 2$ cm.^{3}. This is also the volume of the body. Therefore, the density of the body is $4.8 \div 2 = 2.4$ gm. per cubic centimeter.

Fig. 45

61. Density of Liquids. — A. *By the specific gravity bottle.* A *specific gravity bottle* (Fig. 45) is usually made to hold a definite mass of distilled water at a speci-

fied temperature, for example, 25, 50, or 100 gm. Its volume is therefore 25, 50, or 100 cm.³. To use the bottle, weigh it empty, and filled with the liquid, the density of which is to be determined. The weight of the liquid divided by the capacity of the bottle in cubic centimeters (the number of grams) is equal to the density of the liquid.

B. *By the density bulb.* The *density bulb* is a small glass globe loaded with shot, and having a hook for suspension (Fig. 46). To use it, suspend from the arm of a balance with a fine platinum wire, and weigh first in air and then in water. The apparent loss of weight is the weight of the water displaced by the bulb (§ 55). Then weigh it again when suspended in the liquid. The loss of weight is this time the weight of a volume of the liquid equal to that of the bulb. Divide this loss of weight by the loss in water, and the quotient will be the density of the liquid in grams per cubic centimeter, if the weights are in grams.

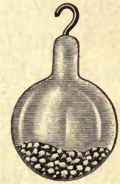


Fig. 46

C. *By the hydrometer.* The common *hydrometer* is usually made of glass, and consists of a cylindrical stem and a bulb weighted with mercury or shot to make it sink to the required level (Fig. 47). The stem is graduated, or has a scale inside, so that readings can be taken at the surface of the liquid in which the hydrometer floats. These readings give the densities directly, or they may be reduced to densities by means of an

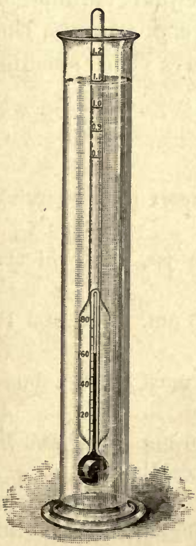


Fig. 47

accompanying table. Hydrometers sometimes have a thermometer in the stem to indicate the temperature of the liquid at the time of taking the reading. Specially graduated instruments of this class are used to test milk, alcohol, acids, etc.

62. Specific Gravity. — *The specific gravity of a body is the ratio between its weight and the weight of an equal volume of water.* If, for example, a cubic inch of iron weighs 7.8 times as much as a cubic inch of water, its specific gravity is 7.8. Also, the density of iron in *c. g. s.* units is 7.8 gm. per cubic centimeter; for, since 1 $cm.^3$ of water weighs 1 gm., 1 $cm.^3$ of iron weighs 7.8 gm. Hence, whatever system of units is used to determine specific gravity, the result will be numerically equal to the density in the *c. g. s.* system, since specific gravity merely expresses how many times heavier a body is than an equal volume of water. If the density is determined in *c. g. s.* units, the numeral expressing the result is always the specific gravity.

Questions and Problems

1. Why does an ocean steamer draw more water after entering fresh water?

2. If the Cartesian diver should sink in the jar, why will the addition of salt cause it to rise?

3. What is the density of a body weighing 15 gm. in air and 10 gm. in water? What is its specific gravity?

4. A hollow brass ball weighs 1 kgm. What must be its volume so that it will just float in water?

5. What is the density of a body weighing 20 gm. in air and 16 gm. in alcohol whose density is 0.8 gm. per cubic centimeter?

6. A bottle filled with water weighed 60 gm. and when empty 20 gm. When filled with olive oil it weighed 56.6 gm. What is the density of olive oil?

7. A density bulb weighed 75 gm. in air, 45 gm. in water, and 21 gm. in sulphuric acid. Calculate the density of the sulphuric acid.

8. A piece of wood weighs 96 gm. in air, 172 gm. in water with sinker attached. The sinker alone in water weighs 220 gm. Find the density of the wood.

9. A piece of zinc weighs 70 gm. in air, and 60 gm. in water. What will it weigh in alcohol of density 0.8 gm. per cubic centimeter?

10. The mark to which a certain hydrometer weighing 90 gm. sinks in alcohol is noted. To make it sink to the same mark in water it must be weighted with 22.5 gm. What is the density of the alcohol?

11. A body floats half submerged in water. What is its specific gravity? What part of it will be submerged in alcohol, specific gravity 0.8?

12. If an iron ball weighs 100.4 lb. in air, what will it weigh in water if its specific gravity is 7.8?

13. What is the specific gravity of a wooden ball that floats two thirds under water?

14. A ferry boat weighs 700 tons. What will be the displacement of water if it takes on board a train weighing 600 tons?

15. A liter flask weighing 75 gm. is half filled with water and half with glycerine. The flask and liquids weigh 1205 gm. What is the density of the glycerine? What is its specific gravity?

IV. PRESSURE OF THE ATMOSPHERE

63. Weight of Air. — It is only a little more than 250 years since it became definitely known that air has any weight at all. Even now we scarcely appreciate its weight.

Place a globe holding about a liter (Fig. 48) on the pan of a balance and counterpoise; the stopcock should be open. Remove the globe and force in more air with a bicycle pump, closing the stopcock to retain the air under the increased pressure; the balance will show that the globe is heavier than before. Remove it again and exhaust the air with an air pump; the balance will now show that the globe has lost weight. A large incandescent lamp bulb may be used in place of the

globe by first counterbalancing and then admitting air by puncturing with the very pointed flame of a blowpipe. Thus air, though invisible, may be put into a vessel or removed like any other fluid; and, like any other fluid, it has weight.


Fig. 48

The weight of a body of air is surprisingly large. A cubic yard of air at atmospheric pressure weighs more than 2 lb. The air in a hall 40 ft. long, 30 ft. wide, and 22.5 ft. high weighs more than a ton. Precise measurements have shown that air at the temperature of freezing and under a pressure equal to that of a column of mercury 76 cm. high weighs 1.293 gm. per liter, or 0.001293 gm. per cubic centimeter. Hydrogen under the same conditions weighs only 0.0000895 gm. per cubic centimeter.

64. Pressure produced by the Air. — Since the air surrounding the earth has weight, it must produce pressure on any surface equal to the weight of a column of air above it, just as in the case of a liquid. Many experiments prove this to be true.

Stretch a piece of sheet rubber, and tie tightly over the mouth of a glass vessel, as shown in Fig. 49. If the air is gradually exhausted from the vessel, the rubber will be forced down more and more by the pressure of the air above it, until it finally bursts. The depression will be the same in whatever direction the rubber membrane may be turned.

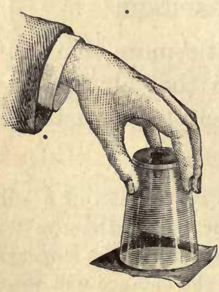


Fig. 50

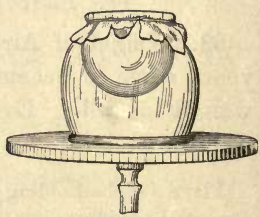


Fig. 49

Fill a common tumbler full of water, cover with a sheet of paper so as to exclude the air, and holding the hand against the paper, in-

vert the tumbler (Fig. 50). When the hand is removed, the paper is held against the mouth of the glass with sufficient force to keep the water from running out.

Cut a piece of glass tubing about 20 cm. long, and 3 or 4 mm. bore. Dip it vertically into a vessel of water, and close the upper end with the finger. The tube may now be lifted out, and the water will remain in it. Figure 51 illustrates a pipette; it is useful for conveying a small quantity of liquid from one vessel to another.

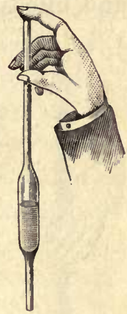


Fig. 51

Take a quart tin can, which should be closed except a small opening, and fill it about one third full of water; boil to expel all the air, and then close the opening air-tight by solder, or in some other equally effective way. Cool with water to condense the steam inside. This leaves a partial vacuum, and the pressure of the atmosphere will cause the can to collapse.

65. The Rise of Liquids in Exhausted Tubes. — Near the close of Galileo's life his patron, the Duke of Tuscany, dug a deep well near Florence, and was surprised to find that he could get no pump in which water would rise more than about 32 feet above the level in the well. He appealed to Galileo for an explanation; but Galileo appears to have been equally surprised, for up to that time everybody supposed that water rose in tubes exhausted by suction because "nature abhors a vacuum." Pumps were well known at that time, and doubtless the Italians were accustomed to take their lemonade by sucking it through a straw, but no explanation of the rise of liquids in exhausted tubes had been given. Galileo suggested experiments to find out to what limit nature abhors a vacuum, but he was too old to perform them himself and died in 1642, before the problem was solved by others.

66. Torricelli's Experiment. — Torricelli, a friend and pupil of Galileo, hit upon the idea of measuring the resistance nature offers to a vacuum by a column of mer-

cury in a glass tube instead of a column of water in the Duke of Tuscany's pump. The experiment was performed in 1643 by Viviani under Torricelli's direction.

A stout glass tube about a meter long, sealed at one end and filled with mercury, is stopped at the open end with the finger, and inverted in a vessel of mercury in a vertical position (Fig. 52). When the finger is removed, the column falls to a height of about 76 cm. The space above the mercury is known as a *Torricellian vacuum*. The column of mercury in the tube is counterbalanced by the pressure of the atmosphere on the mercury in the larger vessel at the bottom.

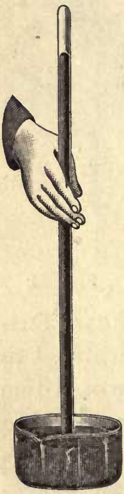


Fig. 52

67. Pascal's Experiments. — To Pascal is due the credit of completing the demonstration that the weight of the column of mercury in the Torricellian experiment measures the pressure of the atmosphere. He reasoned that if the mercury is held up simply by the pressure of the air, the column should be shorter at higher altitudes because there is then less air above it. Put to the test by carrying the apparatus to the top of the "Tour St. Jacques" (Fig. 53),

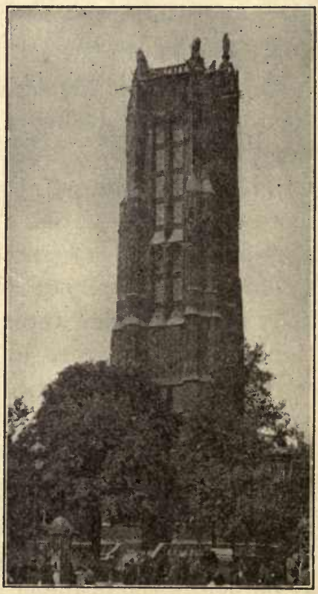


Fig. 53

at that time the bell tower of a church in Paris, his theory was confirmed. Desiring to carry the test still further, he wrote to his brother-in-law to try the experiment on the Puy de Dôme, a mountain nearly 1000 m. high in southern France. The result was that the column of mercury was found to be nearly 8 cm. shorter than in Paris.

Pascal repeated the experiment with red wine instead of mercury, and with glass tubes forty-six feet long; and he found that the lighter the fluid, the higher the column sustained by the pressure of the air. Further, a balloon, half filled with air, appeared fully inflated when carried up a high mountain, and collapsed again gradually during the descent. Thus the question of the Duke of Tuscany was fully answered.

68. Pressure of One Atmosphere. — The height of the column of mercury supported by atmospheric pressure varies from hour to hour; it is dependent also on the altitude above the sea. Its height is independent of the cross section of the tube, but to find the pressure per unit area, a tube of unit cross section must be assumed. Suppose an internal cross sectional area of 1 cm.^{2}. The standard height chosen is 76 cm. of mercury at the temperature of melting ice (0° C.), and at sea level in latitude 45°. The density of mercury at this temperature is 13.596. Hence, *standard atmospheric pressure*, which is the weight of this column of mercury, is

$76 \times 13.596 = 1033.3$ gm. per square centimeter, or roughly 1 kgm. per square centimeter, equivalent to 14.7 lb. per square inch.

The height of a column of water to produce a pressure of one atmosphere is $76 \times 13.596 = 1033.3$ cm. = 33.57 ft.

69. The Barometer. — The *barometer* is an instrument based on Torricelli's experiment, and designed to measure the varying pressure of the atmosphere. In its simplest form it consists of a J-shaped glass tube about 86 cm. (34 in.) high, and attached to a supporting board (Fig. 54). The short arm has a pinhole near the top for the admission of air. A scale is fastened by the side of the tube, and the difference of readings at the top of the mercury in the long and the short arm gives the height of the mercury column sustained by atmospheric pressure. This varies from about 73 to 76.5 cm. for places near sea level. When accuracy is required, the barometer reading must be corrected for temperature. A good barometer must contain pure mercury, and the mercury must be boiled in the glass tube to expel air and moisture.

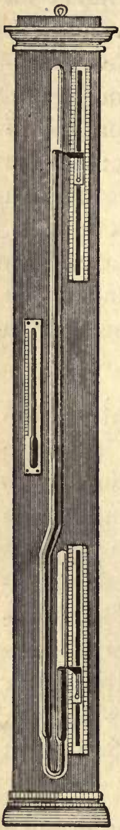


Fig. 54

70. The Aneroid Barometer. — The aneroid barometer contains no liquid. It consists essentially of a shallow cylindrical box *B* (Fig. 55), from which the air is partially exhausted. It has a thin cover corrugated in circular ridges to give it greater flexibility. The cover is prevented from collapsing under atmospheric pressure by a stiff spring attached to the center of the cover at *M*. This flexible cover rises and falls as the pressure of the atmosphere

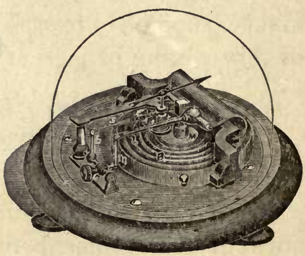


Fig. 55

varies, and its motion is transmitted to the pointer by means of delicate levers and a chain. A scale graduated by comparison with a mercurial barometer is fixed under the pointer. These instruments are so sensitive that they readily indicate the change of pressure when carried from one floor of a building to the next, or even when moved no farther than from a table to the floor.

71. Utility of the Barometer. — The barometer is a faithful indicator of all changes in the pressure of the atmosphere. These may be due to fluctuations in the atmosphere itself, or to changes in the elevation of the observer.

The barometer is constantly used by the Weather Bureau in forecasting changes in the weather. Experience has shown that barometric readings indicate weather changes as follows:

I. *A rising barometer indicates the approach of fair weather.*

II. *A sudden fall of the barometer precedes a storm.*

III. *An unchanging high barometer indicates settled fair weather.*

The difference in the altitude of two stations may be computed from barometer readings taken at the two places simultaneously. Various complex rules have been proposed to express the relation between the difference in barometer readings and the difference in altitude; a simple rule for small elevations is to allow 0.1 in. for every 90 ft. of ascent.

72. Cyclonic Storms. — Weather maps are drawn from observations made at many places at the same time and telegraphed to central stations. In this way cyclonic storms are discovered and followed. At the center of the

storm is the lowest reading of the barometer. Curves of equal pressure (called *isobars*) are traced around this center (Fig. 56). The wind blows from areas of higher pressure toward those of lower, but in the northern hemisphere the inflowing winds are deflected toward the right on account of the rotation of the earth. This gives to the storm a counter-clockwise rotation, as indicated by the arrows in a weather map.

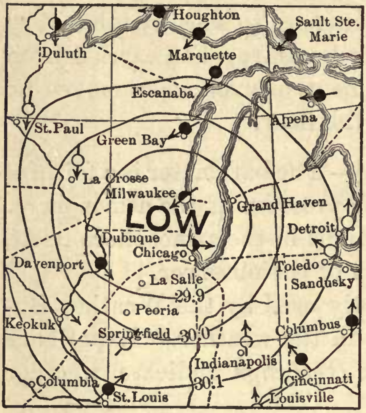


Fig. 56

Cyclonic storms usually cross the northwest boundary of the United States from British Columbia, travel in a southeasterly direction until they cross the Rocky Mountain range, and then turn northeasterly toward the Atlantic coast. Storms coming from the Gulf of Mexico usually travel along the Atlantic coast toward the northeast.

Questions and Problems

1. Why do the ears sometimes hurt when coming down a fast elevator from the top of a tall building?

2. What would be the effect of getting a little air in the top of a barometer tube?

3. What would happen if a minute hole were made in the top of a barometer tube?

4. Why is the reading incorrect if the barometer tube is held in a position inclined to the vertical?

5. A tube 1 ft. long is closed at one end by a sheet of thin rubber tied over it air-tight. It is then filled with mercury and inverted in a vessel of mercury as in Torricelli's experiment. Why does the rubber membrane settle down into the tube?

6. A glass tube 1 ft. long is closed at one end, filled with mercury as in Torricelli's experiment, but instead of resting on the bottom of the vessel, it is suspended from one arm of a balance. Does it weigh more than before it was filled? Give reason.

7. The barometer reading is 75.2 cm. Calculate the atmospheric pressure per square centimeter.

8. The barometer reading is 29 in. Calculate the atmospheric pressure per square inch.

9. Calculate the buoyancy of the air for a ball 10 cm. in diameter if a liter of air weighs 1.29 gm.

10. The density of glycerine is 1.26 gm. per cubic centimeter. If a barometer were constructed for glycerine, what would be its reading when the mercurial barometer reads 75 cm.?

11. When the density of the air is 0.0013 gm. per cubic centimeter, how much less will 200 $cm.^3$ of cork weigh in air than in a vacuum?

12. If a barometer at the foot of a tower reads 29.5 in., while one at the top reads 29.2 in., what is the height of the tower?

Fig. 57

13. A bottle is fitted air-tight with a rubber stopper and a tube as in Fig. 57. If water be sucked out by the tube, what will happen when the tube is released? If air is blown in through the tube, what will happen when the tube is released?

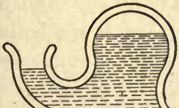


Fig. 58

14. Fig. 58 represents a pneumatic inkstand, nearly full of ink. Why does the ink not run out?

V. COMPRESSION AND EXPANSION OF GASES

73. Compressibility of Air. — All gases are compressed with ease. The inflation of a toy balloon, a pneumatic tire, or an air cushion demonstrates the easy compressibility of the air. It may be shown in a simple way by

pushing a long test tube under water with its open end down. The deeper the tube is sunk, the higher the water rises in it and the smaller becomes the volume of the inclosed air; also the reaction tending to lift the tube increases.

The expansibility of air, or its tendency to increase in volume whenever the pressure is reduced, is shown by its escape from any vessel under pressure, such as the rush of compressed air from a popgun, an air gun, or a punctured pneumatic tire. The air in a building shows the same tendency to expand. When the pressure outside is suddenly reduced, as in the passage of a wave due to an explosion, the force of expansion of the air within often bursts the windows outward.

Blow air into the bottle (Fig. 57) through the open tube. The air forced in bubbles up through the water and is compressed within. As soon as the tube is released and the pressure in it falls to that of the atmosphere, the expansive force of the imprisoned air forces water out through the tube with great velocity.

The compression and the expansion of air are both illustrated by the common pneumatic door check for light doors; also by the air dome on a force pump, and the air cushion on a water pipe, which is usually carried a few inches higher than the faucet so that the air confined in the closed end may act as a cushion to take up any sudden shock due to the inertia of the water when the stream is suddenly checked. The "pounding" of the pipes when the water is suddenly turned off is owing to the absence of this air cushion.

74. Boyle's Law. — The relation between the volume of a confined mass of air and the pressure it sustains was discovered by Robert Boyle in Oxford, and announced by him in 1662.

Boyle's experiments were made with a J-tube (Fig. 59); and they extended only from $\frac{1}{24}$ of an atmosphere to 4 atmospheres pressure. The short leg A was closed at the top and mercury was poured in until it stood at the same level in both legs of the tube. The air in

the short leg was then under the same pressure as the atmosphere outside. Its volume was noted by means of the attached scale, and more mercury was then poured into the tube. The difference in the level of the mercury in the two legs of the tube gave the excess of pressure on the inclosed air above that of the atmosphere. When this difference amounted to 76 cm., the pressure on the gas in the short tube was 2 atmospheres, and its volume was reduced to one half. When the difference became twice 76 cm., the pressure on the enclosed air was 3 atmospheres and its volume became one third; and so on.

Fig. 59

This is the law of the compressibility of gases; it is known as Boyle's law and may be expressed as follows:

At a constant temperature the volume of a given mass of gas varies inversely as the pressure sustained by it.

If the volume of gas v under a pressure p becomes volume v' when the pressure is changed to p', then by the law

$$\frac{v}{v'} = \frac{p'}{p}; \text{ whence } pv = p'v'. \qquad \text{(Equation 3)}$$

In other words, *the product of the volume of the gas and the corresponding pressure remains constant for the same temperature.*

75. The Law Approximate. — Extended investigation has shown that Boyle's law is not rigorously exact, even for air at moderate pressures. In general, gases are more compressible than the law requires. Such gases as oxygen and nitrogen show a minimum value for the product pv; beyond this minimum value an increase of pressure causes the product pv to increase. For hydrogen the

value of pv is always higher than it would be if Boyle's law were precisely true. But within moderate limits of pressure and at ordinary temperatures, Boyle's law is extremely useful as a working relation.

An example will illustrate its use: If a mass of gas under a pressure of 72 cm.^{3} of mercury has a volume of 1900 cm.^{3}, what would its volume be if the pressure were 76 cm.^{3}? By equation (3), $pv = p'v'$; hence, $72 \times 1900 = 76 \times v'$. From this equation $v' = 1800$ cm.^{3}.

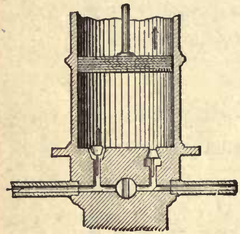


Fig. 60

76. The Air Compressor. — A pump designed to compress air or other gases under a pressure of several atmospheres is shown in section in Fig. 60, and complete in Fig. 61. The piston is solid, and there are two metal valves at the bottom. Air or other gas is admitted through the left-hand tube when the piston rises; when it descends, it compresses the inclosed air, the pressure closes the left-hand valve, and opens the outlet valve on the right, and the compressed air is discharged into the compression tank.

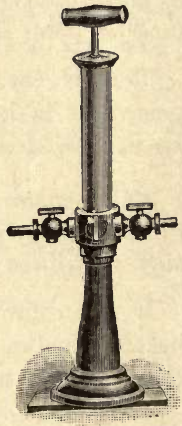


Fig. 61

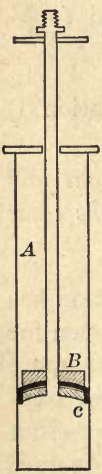


Fig. 62

A bicycle pump (Fig. 62) is an air compressor of a very simple type. The piston has a cup-shaped leather collar c, which permits the air to pass by into the cylinder when the piston is withdrawn, but closes when the piston is forced in. The collar thus serves as a valve, allowing the air to flow one way but not the other. The

compressed air is forced through the tube forming the piston rod, and the check valve in the tire inlet prevents its return.

77. The Air Pump. — The *air pump* for removing air or any gas from a closed vessel depends for its action on the expansive or elastic force of the gas. The first air pump was invented by Otto von Guericke, burgomaster of Magdeburg, about 1650. In the very simplest form the two valves, corresponding with those of the air compressor, are worked by the pressure of the air. But though they may be made of oiled silk and very light, the pressure in the vessel to be exhausted soon reaches a lower limit below which it is too small to open the valve between it and the cylinder of the pump. On this account automatic valves, operated mechanically, are in use on the better class of pumps.

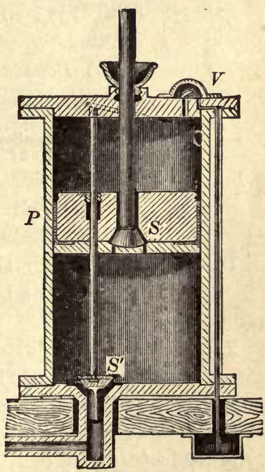


Fig. 63

Figure 63 shows the inside of one of the simpler forms with automatic valves. A piston P, with a valve S in it, works in a cylindrical barrel, communicating with the outer air by a valve V at its upper end, and with the receiver to be exhausted by the horizontal tube at the bottom. The valve S' is carried by a rod passing through the piston, and fitting tightly enough to be lifted when the upstroke begins. The ascent of the rod is almost immediately arrested by a stop near its upper end, and the piston then slides on the rod during the remainder of the upstroke. The open valve S' allows

the air to flow from E into the space below the piston. At the end of the upstroke the valve S' is closed by the lever shown in dotted lines. During the downward movement the valve S is open, and the inclosed air passes through it into the upper part of the cylinder. The ascent of the piston again closes S; and as soon as the air is sufficiently compressed, it opens the valve V and escapes. Each complete double stroke removes a cylinder full of air; but as it becomes rarer with each stroke, the mass removed each time grows less.

78. Experiments with the Air Pump. — 1. *Expansibility of air.*

(*a*) *Football.* Fill a small rubber football half full of air, and place under a bell jar on the table of the air pump. When the air is exhausted from the jar, the football expands until it is free from wrinkles. A toy balloon may be substituted.

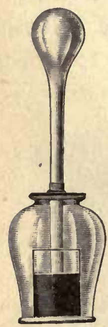


Fig. 64

(*b*) *Bolthead.* A glass tube with a large bulb blown on one end (Fig. 64) is known as a *bolthead.* The stem passes air-tight through the cap of the bell jar, and dips below the surface of the water in the inner vessel. When the air is exhausted from the jar, the air in the bolthead expands and escapes in bubbles through the water. Readmission of air into the jar restores the pressure, and drives water into the bolthead.

2. *Air pressure.* (*a*) *Downward.* Wet a piece of parchment, and tie it tightly over the mouth of a glass cylinder (Fig. 65). A piece of parchment paper may be pasted over the cylinder instead. When the air is exhausted, the parchment or the paper will break with a loud report.

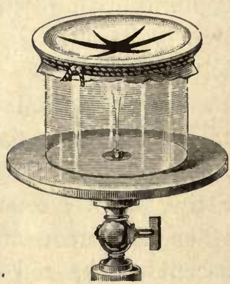


Fig. 65

(*b*) *The vacuum fountain.* A tall glass vessel has an inner jet tube which may be closed on the outside with a stopcock. (A stout bottle

with a rubber stopper and a jet tube may be substituted.) Exhaust the air, place the opening into the jet tube in water, and open the stopcock. The water is forced by atmospheric pressure into the exhausted tube like a fountain (Fig. 66).

(*c*) *Upward pressure.* A strong glass cylinder is fitted with a piston, and is supported on a tripod (Fig. 67). The brass cover of the cylinder is connected with the air pump by a thick rubber tube. When the air is exhausted, the piston is lifted by atmospheric pressure, and carries the heavy attached weight.

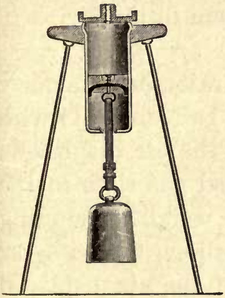


Fig. 67

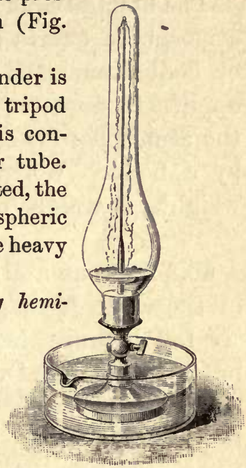


Fig. 66

(*d*) *The Magdeburg hemispheres.* This historical piece of apparatus was designed by Otto von Guericke to exhibit the great pressure of the atmosphere (Fig. 68). The lips of the two parts are accurately ground to make an air-tight joint when greased. When they are brought together and the air is exhausted, it requires considerable force to pull them apart. The original hemispheres of von Guericke were about 1.2 ft. in diameter, and the atmospheric pressure holding them together was about 2400 lb.

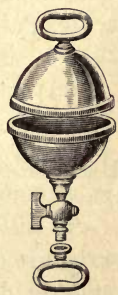


Fig. 68

79. Buoyancy of the Air. — A small beam balance has attached to one arm a hollow closed brass globe ; it is counterbalanced in air by a solid brass weight on the other arm. (A large cork or a glass float may be substituted for the globe, and a piece of lead for the brass weight.) When the

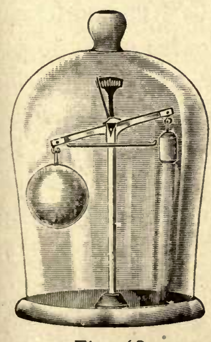


Fig. 69

balance is placed under a bell jar, and the air is exhausted, the globe overbalances the solid weight (Fig. 69).

The apparatus is called a *baroscope*. It shows that the atmosphere exerts an upward pressure or buoyant force on bodies immersed in it; for the principle of Archimedes applies to gases as well as to liquids. The buoyancy of the atmosphere is equal to the weight of the air displaced by a body. Whenever a body is less dense than the weights, it weighs more in a vacuum than in the air.

80. Balloons and *airships* also illustrate the buoyancy of the air. A soap bubble and a toy balloon filled with air fall because they are heavier than the air displaced; but a bubble filled with hydrogen or coal gas rises in the air. Its buoyancy is greater than its weight, including the inclosed gas. The weight of a balloon with its car and contents must be less than that of the air displaced by it. The essential part of a balloon is a silk bag, varnished to make it air-tight; it is filled either with hydrogen or with illuminating gas. A cubic meter of hydrogen weighs about 0.09 kgm., a cubic meter of illuminating gas, 0.75 kgm., while a cubic meter of air weighs 1.29 kgm. (§ 63). With hydrogen the buoyancy is $1.29 - 0.09 = 1.2$ kgm. per cubic meter; with illuminating gas it is $1.29 - 0.75 = 0.54$ kgm. per cubic meter. The latter is more commonly used because it is much cheaper.

A balloon is not fully inflated to start with, but it expands as it rises because the pressure of the air on the outside diminishes. The buoyancy then decreases only slowly as the balloon ascends into a rarer atmosphere. If it were fully inflated at the start, the inside pressure of the gas as the balloon ascends would be greater than the diminishing atmospheric pressure, and the bag would

almost certainly burst before any great altitude was reached.

One of the most noted long distance balloon journeys was that of Count de la Vaulx, in 1900, who traveled from Paris into Russia, a distance of 1193 miles, in 35 hr. 45 min. The greatest altitude reached was 18,700 ft. The balloon United States, which won the first international race at Paris in 1906, was filled with more than 2000 cubic meters of illuminating gas, with a lifting force of 1000 kgm., or 2200 lb.

Problems

1. A certain mass of gas under a pressure of one atmosphere has a volume of 6000 l. To how many atmospheres must the pressure be increased to reduce the volume to 1000 liters?

2. A steel tank having a capacity of 3 cu. ft. is filled with oxygen under a pressure of 10 atmospheres. How much gas is in the tank estimated at standard atmospheric pressure?

3. A liter of air at 0° C. and under a pressure of 76 cm. weighs 1.29 gm. How much would a liter weigh if the barometric pressure were reduced to 72 cm.? (The mass varies directly as the pressure.)

4. An open vessel contains 200 gm. of air when the pressure is 74 cm. How much would it contain if the pressure were 76 cm.?

5. The volume of hydrogen collected over mercury in a graduated cylinder was 50 cm.^{3}, the mercury standing 15 cm. higher in the cylinder than outside of it. The reading of the barometer was 75 cm. How many cubic centimeters of hydrogen would there be at a pressure of 76 cm.?

Suggestion. The height of the mercury in the cylinder above the surface of the mercury outside must be subtracted from the barometer reading to get the pressure of the gas in the cylinder.

6. A test tube is forced down into water with its open end down, until the air in it is compressed into the upper half of the tube. How deep down is the tube if the barometer stands at 30 in.? (The specific gravity of mercury may be taken as 13.6.)

7. What part of the air is left in a bell jar on an air pump when the mercury in the gauge is 2 in. higher on one side than on the other, if the barometer stands at 30 in.?

8. What will be the difference in the heights of the mercury columns in the gauge when $\frac{1}{750}$ of the air is left in the receiver?

9. With what volume of illuminating gas must a balloon be filled in order to rise, if the empty balloon and its contents weigh 540 kgm.?

10. A mass of iron, density 7.8, weighs 2 kgm. in air. How much will it weigh in a vacuum?

VI. PNEUMATIC APPLIANCES

81. The Siphon. — The siphon is a U-shaped tube employed to convey liquids from one vessel to another at a lower level by means of atmospheric pressure. If the tube is filled and is placed in the position shown in Fig. 70, the liquid will flow out of the vessel and be discharged at the lower level *D*.

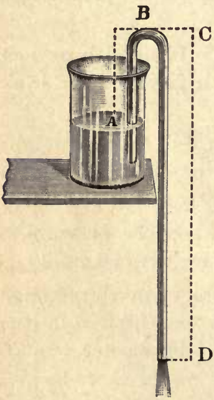


Fig. 70

If the liquid flows outward past the highest point of the tube in the direction *BC*, it is because the pressure on the liquid outward is greater than the pressure in the other direction. Now the outward pressure at the top is the pressure of the atmosphere minus the weight of the column of liquid *AB*; while the pressure inward is atmospheric pressure minus the weight of the column *DC*. Hence, the pressure inward is less than the pressure outward by the weight of a column of the liquid equal in height to the difference between *AB* and *DC*. The siphon will cease to act when the liquid reaches the lower end of the shorter arm *AB*, or if the liquid flows into another vessel, when the level is the same in the two vessels. It will also fail to act in

water when the bend of the tube is more than about 33 feet above the surface of the water at A.

An intermittent siphon (Fig. 71) has its short arm inside a vase and its long arm passing through the bottom. The vase will hold water until its level reaches the top of the bend of the siphon. It then discharges and empties the vessel, if it discharges faster than it is filled. Again the water rises in the vase, and the siphon again empties it. Intermittent springs are supposed to operate on the same principle.

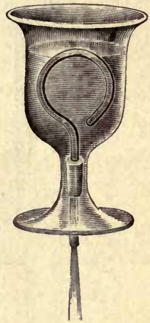


Fig. 71

A so-called vacuum siphon may be made with a Florence flask and glass tubing (Fig. 72). The flask is partly filled with water, and the apparatus is then inverted as shown. The water enters the flask as a jet. If a piece of rubber tubing is attached to the longer arm, the jet will rise as the end of the tubing is lowered. A portion of the water runs out at first, producing a partial vacuum inside.

Fig. 72

A siphon made of glass tubing about 2 mm. in diameter, may be set up with mercury as the liquid. If it is set in action under a tall bell jar on the air pump, it will stop working when the air is exhausted from the jar, but will begin again when the air is admitted.

The water of an S-trap, in common use under sinks and washbowls, may be siphoned off when the discharge pipe is filled with water for a short distance below the trap, unless the trap is ventilated at the top of the S.

82. The Lift Pump. — The common suction pump acts by the pressure of the air; it is, in fact, a simple form of air pump; but it was in use 2000 years before the air pump was invented. The first few strokes serve merely to exhaust air from the pipe below the valve V (Fig. 73); the pressure of the air on the water in the well or cistern

then forces it up the pipe S, and finally through the valve V. After that, when the piston descends, the valve V closes under water, and water passes through the valve V above the piston. The next upstroke lifts the water to the level of the spout. Since the pressure of the air lifts the water to the highest point to which the piston ascends, it is obvious that this point can not be more than the limit of about 33 ft. above the water in the well. Practically it is less on account of leakage through the imperfect valves. The priming of a pump by pouring in a little water to start it serves to wet the valves and make them air-tight.

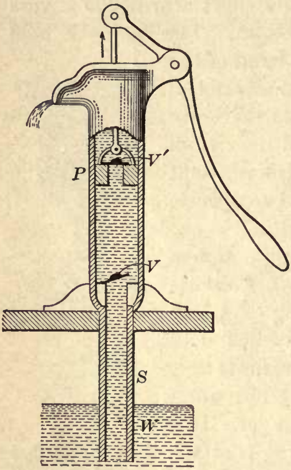


Fig. 73

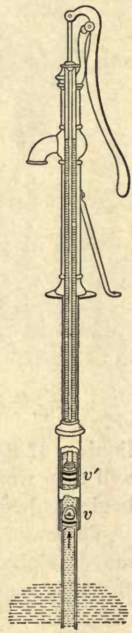


Fig. 74

For deep wells the common pump is modified by placing the piston and the valves v and v' far down the well; a long pump rod serves to lift the water from the piston to the spout (Fig. 74).

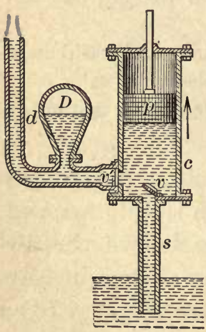


Fig. 75

83. The Force Pump. — The *force pump* (Fig. 75) is used to deliver water under pressure, either at a point higher than the pump into pipes, as in the fire

engine and the hydraulic press, or into boilers under pressure of the steam. The construction is obvious from the figure.

The air dome *D* is added to secure a continuous flow through the delivery pipe *d*. Water flows out through v' only while the piston is descending; without the air dome, therefore, water would flow through the pipe *d* only during the downstroke of the piston; but the water under pressure from the piston enters the dome and compresses the air. The elastic force of the air drives the water out again as soon as v' closes. Thus the flow is continuous.

The pump of a steam fire engine is double acting, that is, it forces water out while the piston is moving in either direction; so also are pumps for waterworks and mines.

84. The Air Brake. — The well-known Westinghouse *air brake* is operated by compressed air. In Fig. 76, *P* is the train pipe leading to a large reservoir at the engine, in which an air compressor maintains a pressure of about 75 lb. per square inch. So long as this pressure is applied through *P*, the automatic valve *V* maintains communication between *P* and an auxiliary reservoir *R* under each car, and at the same time shuts off air from the brake cylinder *C*. But as soon as the pressure in *P* falls, either by the movement of a lever in the engineer's cab or by the accidental parting of the hose coupling *k*, the valve *V* cuts off *P* and connects the reservoir *R* with the cylinder *C*. The pressure on the piston in *C* drives it powerfully to the left and sets the brake shoes against the wheels. As soon as air from the main reservoir is

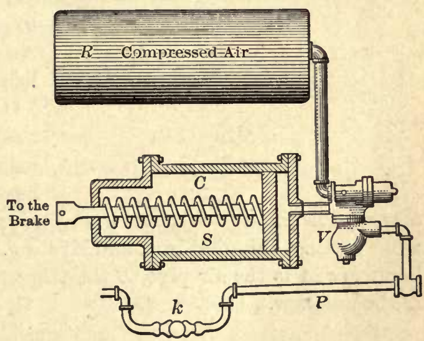


Fig. 76

again admitted to the pipe P, the valve V re-establishes communication between P and R, and the confined air in C escapes. The brakes are released by the action of the spring S in forcing the piston back to the right.

85. Other Applications of the Air Pump and the Air Compressor. — The air pump and the air compressor are extensively used in industry. Sugar refiners employ the air pump to reduce the boiling point of the syrup; manufacturers of soda water use a compressor to charge the water with carbon dioxide; in pneumatic dispatch tubes, now extensively used for carrying small packages, both pumps are used, one to exhaust the air from the tube in front of the closely fitting carriage, and the other to compress air in the tube behind it, so as to propel the carriage with great velocity. The air compressor is employed to make a forced draft for steam boilers, to ventilate buildings, and to operate machinery in places difficult of access, as in mines, where it furnishes fresh air as well as power. It is employed also in the pneumatic *caisson* for making excavations and laying foundations under water. The caisson is a large heavy air chamber which sinks as the soft earth is removed from within. When its bottom is below water level, air is forced in under sufficient pressure to prevent the entrance of water. Access to it is gained by air-tight locks.

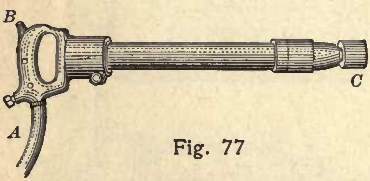


Fig. 77

Compressed air is frequently used for operating railway signals, and to control automatic heating and ventilating appliances. Pneumatic tools are used for calking seams and joints, for stone cutting, chipping iron, and riveting. Figure 77 shows a riveting hammer; A is the air pipe, B the trigger for controlling the air, and C the hammer.

CHAPTER IV

MOTION

I. MOTION IN STRAIGHT LINES

86. Types of Motion. — *Motion is the change in the relative position of a body* with respect to some point, line, or place of reference. A body is *at rest* when its relative position remains unchanged. All rest and motion *are relative only*, since there are no fixed points or lines in space to which absolute motion may be referred.

The moving about of a person on a ship is relative to the vessel; the movement of the ship across the ocean is relative to the earth's surface; the daily motion of the earth's surface is relative to its axis of rotation; the motion of the earth as a whole is relative to the sun; while the sun itself is drifting with other stars through space.

The motion of a body is *rectilinear* when it moves along a straight line; *curvilinear* when its path is a curved line. Then there is also *simple harmonic motion*, exemplified by the to-and-fro swing of a pendulum; and *rotary motion* about an axis, such as the rotation of the earth on its axis, and that of the pulley and armature of a stationary electric motor. The motion of a carriage wheel along a level road, and that of a ball along the floor of a bowling alley combine motion of rotation with rectilinear motion.

87. Velocity. — *Velocity is the rate of motion*, that is, it is the distance traversed per unit of time. In expressing a velocity the unit of time must be given as well as the number denoting the velocity; for example, 44.7 centi-

meters per second, 5280 feet per minute, or 60 miles per hour. These are all different expressions for the same velocity or rate of motion.

If the motion is over equal distances in equal and successive periods of time, the motion is *uniform*, and the velocity is *constant;* otherwise the velocity is *variable*, and the motion is either *accelerated* or *retarded.* When there is a gain in velocity from instant to instant, the motion is said to be *accelerated;* when there is a loss, it is *retarded.* A retardation is counted as a negative acceleration. When an electric street car starts from rest, its motion is accelerated until it reaches top speed; in going up a grade, or nearing a sharp curve, or slowing down to stop at a station or crossing, its motion is retarded.

88. Uniform Motion. — Since velocity, denoted by v, is the distance traversed per unit of time, then in *uniform motion* it must be equal to the whole distance s traversed divided by the number of units of time t spent in traversing that distance. Whence

$$velocity = \frac{distance}{time}.$$

In symbols this is written, $v = \frac{s}{t}$; from which

$$s = vt \text{ and } t = \frac{s}{v}. \quad . \quad . \quad \text{(Equation 4)}$$

These three simple equations express in order the following relations between velocity, distance, and time in uniform motion:

1. *The velocity in uniform motion is the quotient of the whole distance traversed by the time of traversing it.*

2. *The distance traversed in uniform motion is the product of the velocity and the time.*

3. *The time required to traverse a given distance in uniform motion is the quotient of the distance by the velocity.*

EXAMPLE. A railway train runs uniformly covering 660 ft. in 10 min. Then $v = \frac{660}{10} = 66$ ft. per minute or $\frac{3}{4}$ mi. per hour. The distance $s = 66 \times 10 = 660$ ft. The time $t = \frac{660}{66} = 10$ min.

89. Velocity at any Instant. — When the motion is variable, the velocity of a body *at any instant* is the distance it would travel in the next unit of time if at that instant its motion were to become *uniform.*

For example: The velocity of a falling body at any moment is the distance it would fall during the following second, *if the attraction of the earth and the resistance of the air were both to be withdrawn.* The velocity of a ball as it leaves the muzzle of a gun is the distance it would pass over in the second following *if from that instant it should continue to move for a second without any change in speed.* Actually the motion of the body and the ball for the succeeding second is *variable;* the inquiry is, what would be the velocity if the motion were *invariable?*

90. Acceleration. — When a train runs a mile a minute for several minutes, it moves with uniform velocity; but when it is starting or slowing down, it is said to be *accelerated.* If the velocity increases, the acceleration is *positive;* if it decreases, it is *negative.* A falling body goes faster and faster; it has a positive acceleration. A body thrown upward goes more and more slowly; it has a negative acceleration. A loaded sled starts from rest at the top of a long hill; it gains in velocity as it descends the hill; it has a positive acceleration. When it reaches the bottom, it loses velocity and is retarded, or has a negative acceleration, until it stops. *Acceleration is the rate of change of velocity.* It is the change in velocity per unit of time.

If the change in velocity is the same from second to second, the motion is *uniformly accelerated.* The best example we have of uniformly accelerated motion is that of a falling body, such as a stone or an apple. Neglecting the resistance of the air, its gain in velocity is 9.8 m. *per second* for *every second it falls.* Its acceleration is therefore 9.8 m. *per second per second;* in other words, it gains in velocity 9.8 m. *per second* for *every second* of time. This is equivalent to an increase in velocity of 588 m. *per second* acquired in a *minute* of time. The unit of time enters twice into every expression for acceleration, the first to express the change in velocity, and the second to denote the interval during which this change takes place.

If an automobile starts from rest and increases its speed one foot a second for a whole minute, its velocity at the end of the minute is 60 ft. per second. Since it gains in one second a velocity of one foot a second, and in one minute a velocity of 60 ft. a second, its acceleration may be expressed either as one foot per second per second, or as 60 ft. per second per minute. Its velocity is constantly changing; its acceleration is constant.

91. Velocity in Uniformly Accelerated Motion. — Suppose a body to move from rest in any given direction with a constant acceleration of 5 ft. per second per second. Its velocity at the end of the first second will be 5 ft. per second; at the end of two seconds, 2×5 ft.; at the end of three seconds, 3×5 ft.; and at the end of t seconds, $t \times 5$ ft. per second; that is,

$$\textit{final velocity} = \textit{time} \times \textit{acceleration},$$

or in symbols,

$$v = ta; \text{ whence } a = \frac{v}{t}. \quad . \quad . \quad (\text{Equation } 5)$$

92. Distance traversed in Uniformly Accelerated Motion. — If we can find the *mean* or *average* velocity for any period of t seconds, the distance s traversed in t seconds may be found precisely as in the case of uniform motion (§ 88). For a body starting from rest with an acceleration of 5 ft. per second per second, for example, its velocity at the end of four seconds is 4×5 ft. per second, and the average velocity for the four seconds is one half of 4×5, or 2×5 ft. per second, the velocity at the middle of the period. So at the end of t seconds the average velocity is $\frac{1}{2}ta$ ft. per second. Then we have

$$distance = average\ velocity \times time,$$

or in symbols,

$$s = \tfrac{1}{2}ta \times t = \tfrac{1}{2}at^2 \quad . \quad . \quad \text{(Equation 6)}$$

From the last two articles we derive the following laws for uniformly accelerated motion:

I. *In uniformly accelerated motion the velocity attained in any given time is proportional to the time.*

II. *In uniformly accelerated motion the distance traversed is proportional to the square of the time.*

93. Uniformly Accelerated Motion Illustrated. — The oldest method of demonstrating uniformly accelerated motion was devised by Galileo. It consists of an inclined plane two or three meters long (Fig. 78), made of a straight board with a shallow groove, down which a marble may roll slowly enough to permit the distances to be noted. For measuring time,

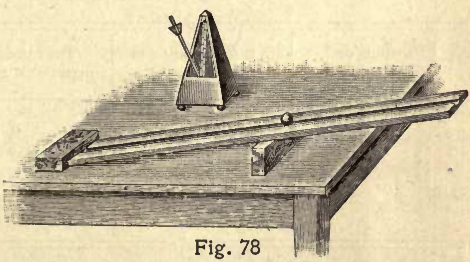


Fig. 78

a clock beating seconds, or a metronome, may be used. Assume a metronome as shown in the figure. One end of the board should be elevated until the marble will roll from a point near the top to the bottom in three seconds.

Hold the marble in the groove against a straightedge in such a way that it may be quickly released at a click of the metronome. Find the exact position of the straightedge near the top of the plane from which the marble will roll to the bottom and strike the block there so that the blow will coincide with the third click of the metronome after the release of the marble. Measure exactly the distance between the upper edge of the straightedge and the block at the bottom and call it $9d$. Next, since distances are proportional to the square of the times, let the straightedge be placed at a distance of $4d$ from the block; the marble released at this point should reach the block at the second click of the metronome after it starts. Finally, start the marble against the straightedge at a distance d from the block; the interval this time should be that of one beat of the metronome, which should be adjusted to beat approximately seconds.

TABULAR EXHIBIT

NUMBER OF SECONDS, t	WHOLE DISTANCE FALLEN, s	DISTANCE IN SUCCESSIVE SECONDS	VELOCITIES ATTAINED, v
1	d	d	$2d$
2	$4d$	$3d$	$4d$
3	$9d$	$5d$	$6d$
4	$16d$	$7d$	$8d$

The third column is derived by subtracting the successive numbers of the second. To get the fourth column,

we notice that if t is one second in equation (6), then $s = \frac{1}{2}a$; that is, *the distance traversed in the first second is one half the acceleration.* But the acceleration is the same as the velocity acquired the first second. Hence $s = \frac{1}{2}v$ and $d = \frac{1}{2}v$. Therefore the velocity at the end of the first second on the inclined plane is $2d$. Since by equation (5) the velocities are proportional to the time, the succeeding velocities are $4d$, $6d$, etc.

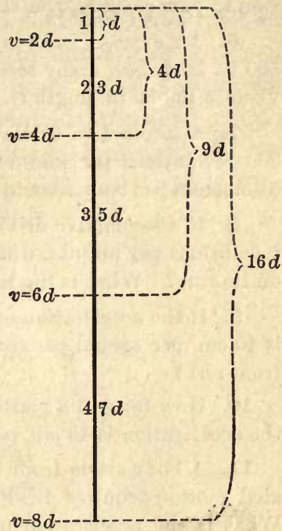


Fig. 79

The numbers in the second column show that the distances traversed are proportional to the squares of the time [compare equation (6)]; those of column three show that the distances in successive seconds are as the odd numbers 1, 3, 5, etc. The results may be shown graphically as in Fig. 79.

Problems

NOTE. For the relation between the circumference of a circle and its diameter, see the Mensuration Table in the Appendix.

1. An aviator drives his aëroplane through the air a distance of 500 km. in 8 hr. 20. min. What was his average speed per minute?

2. The engine drives a boat downstream at the rate of 15 mi. an hour, while the current runs 3 ft. a second. How long will it take to go 50 mi.?

3. A man runs a quarter of a mile in 48.4 seconds. At that speed, what was his time for 100 yd.?

4. If a man can run 100 yd. in 10 sec., what would be his time for a mile, if it were possible to maintain the same speed? Compare the result with the record for a mile.

5. A procession 100 yd. long, moving at the rate of 3 mi. an hour, passes over a bridge 120 yd. long. How long does it take the procession to pass entirely over the bridge?

6. An express train is running 60 mi. an hour. If the train is 500 ft. long, how many seconds will it be in passing completely over a viaduct 160 ft. in length?

7. A locomotive driving wheel is 2 m. in diameter. If it makes 200 revolutions per minute, what is the speed of the locomotive in kilometers per hour, assuming no slipping of the wheels on the track?

8. If a locomotive driving wheel 2 m. in diameter is making 200 revolutions per minute, what is the greatest linear velocity of a point on its rim? What is the least?

9. If the acceleration of a marble rolling down an inclined plane is 40 cm. per second per second, what will be its velocity after 3 sec. from rest?

10. How far will a marble travel down an inclined plane in 3 sec. if the acceleration is 40 cm. per second per second?

11. A body starts from rest, and moving with uniformly accelerated motion acquires in 10 sec. a velocity of 3600 m. per minute. What is the acceleration per second per second. How far does the body go in 10 sec.?

12. What acceleration per minute per minute does a body have if it starts from rest and moves a distance of a mile in 5 min.? What will be its velocity at the end of 4 min.?

13. If a train acquires in 2 min. a velocity of 60 mi. an hour, what is its acceleration per minute per minute, assuming uniformly accelerated motion?

14. An electric car starting from rest has uniformly accelerated motion for 3 min. At the end of that time its velocity is 27 km. per hour. What is its acceleration per minute per minute?

15. A sled is pushed along smooth ice until it has a velocity of 4 m. per second. It is then released and goes 100 m. before it stops. If its motion is uniformly retarded, what is the retardation in centimeters per second per second?

16. To acquire a speed of 60 mi. an hour in 10 min., how far would an express train have to run, provided it started from rest and its motion were uniformly accelerated?

II. CURVILINEAR MOTION

94. Direction of Motion on a Curve. — *Curvilinear motion*, or *motion along a curved line*, occurs more frequently in nature than motion in a straight line. The motion of a point on the earth's surface and about its axis is in a circle; the motion of the earth in its path around the sun is along a curve only approximately circular; the motion of a rocket or of a stream of water directed obliquely upward is along a parabolic curve, the same as the path of many comets. So also is the motion of a baseball when batted high in air. The thrown "curved ball," too, illustrates curvilinear motion.

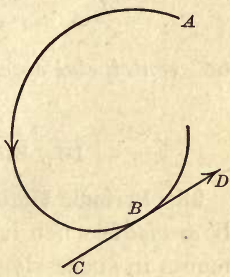


Fig. 80

When the motion is along a curved line, the direction of motion *at any point*, as at B (Fig. 80), is that of the line CD, tangent to the curve at the point. This is the same as the direction of the curve at the point.

95. Uniform Circular Motion. — In uniform circular motion the velocity of the moving body, measured along the circle, is constant. There is then no acceleration in the direction in which the body is going at any point. But while a velocity may remain unchanged in value, *it may vary in direction.* If a body is moving with constant velocity in a straight line, its acceleration is zero *in every direction;* but *if the direction of its motion changes continuously*, then there is an acceleration *at right angles to its path* and its motion becomes *curvilinear.* If this acceleration is constant, the motion is uniform in a circle. Hence, *in uniform circular motion there is a con-*

stant acceleration directed toward the center of the circle. It is called *centripetal acceleration.*

Uniform circular motion consists of a uniform motion around the circumference of the circle and a uniformly accelerated motion along the radius. If v is the uniform velocity around the circle whose radius is r, the value of the *centripetal acceleration* is

$$a = \frac{v^2}{r},^* \quad . \quad . \quad . \quad . \quad \text{(Equation 7)}$$

or $$\textit{centripetal acceleration} = \frac{\textit{square of velocity in circle}}{\textit{radius of circle}}.$$

III. SIMPLE HARMONIC MOTION

96. Periodic Motion. — The motion of a body is said to be *periodic* when it goes through the same series of movements in successive equal periods of time. If the motion returns periodically to the same value and is as often reversed in direction, it is said to be *vibratory.* The motion of the earth around the sun is periodic, but not vibratory. A hammock swinging in the wind, the pendulum of a

*Let ABC (Fig 81) be the circle in which the body revolves, and AB the minute portion of the circular path described in a very small interval of time t. Denote the length of the arc AB by s. Then, since the motion along the arc is uniform, $s = vt$. AB is the diagonal of a very small parallelogram with sides AD and AE. The latter is the distance through which the revolving body is deflected toward the center while traversing the *very small arc* AB. Since the acceleration is constant, $AE = \frac{1}{2}at^2$ by equation (6). The two triangles ABE and ABC are similar. Hence $\overline{AB}^2 = AE \times AC$. Calling the radius of the circle r and substituting for AB, AE, and AC their values, $v^2t^2 = \frac{1}{2}at^2 \times 2\,r = at^2r$. Then $a = \frac{v^2}{r}$.

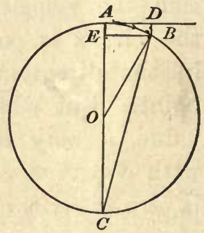


Fig. 81

clock, a bowed violin string, and the prong of a sounding tuning fork illustrate both periodic and vibratory motion.

97. Simple Harmonic Motion Described.—Simple harmonic motion is a name given to all pendular motions of small amplitude. The name appears to be due to the fact that simple musical sounds are caused by bodies vibrating in this manner.

Suspend a ball by a long thread and set it swinging in a horizontal circle (Fig. 82). Place a white screen back of the ball; standing several feet away and with the eye E on a level with the ball, watch its moving projection on the screen. The eye discerns the motion to the right and to the left, but not the motion toward the observer and away from him. The apparent motion of the ball, as viewed against the screen, is *simple harmonic*.

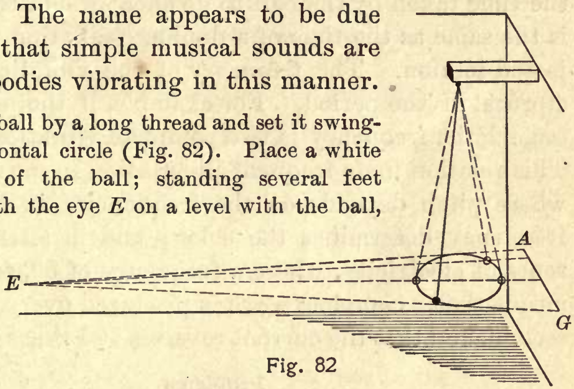


Fig. 82

Though the ball is moving uniformly around the circle, its projected motion is vibratory. The velocity of this simple harmonic motion is greatest at the middle of its path AG, and decreases to zero at either extremity.

Let the circle of Fig. 83 represent the path of the ball, and $ABCD$, etc., its projection on the screen. When the ball moves along the arc adg, it appears to the observer to move from A through B, C, etc., to G, where it momentarily comes to rest. It then starts back toward A, at first very slowly, but with increasing velocity until it passes D. Its velocity then decreases, and at A it is again zero, and the motion

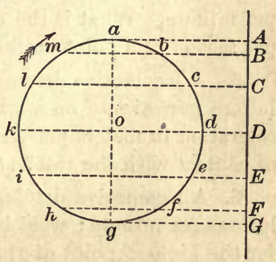


Fig. 83

reverses. At k and d the ball is moving across the line of sight and the apparent motion on the screen is the fastest.

The radius of the circle, or the distance AD, is the *amplitude* of the vibration. The *period* of the motion is the time taken by the ball to go once around the circle; it is the same as the time of a double oscillation of the projected motion. The *frequency* of the vibration is the reciprocal of the period. For example, if the period is $\frac{1}{2}$ a second, the frequency is two complete vibrations a second. This relation finds frequent illustration in musical sounds, where pitch depends on the frequency; in light, where frequency determines the color; and in alternating currents of electricity, where a frequency of 50, for example, means that a complete wave is produced every fiftieth of a second, and that the current reverses 100 times per second.

Problems

1. At what speed must a cyclist ride around a circular track one mile in diameter in order to go around it in half an hour?

2. The circumference of the earth at the equator is about 25,000 mi. What is the linear velocity in feet per second of a point on the equator, owing to the earth's rotation on its axis?

3. The diameter of the 40th degree parallel of latitude is about 6000 mi. What is the speed in feet per second of a point on this parallel on account of the earth's rotation on its axis?

4. A flywheel 6 ft. in diameter runs at the rate of 60 revolutions per minute. What is the centripetal acceleration in feet per second per second of a point on the outer rim of the wheel?

5. A locomotive driving wheel 2 m. in diameter makes 200 revolutions per minute on a straight track. What is the centripetal acceleration in meters per second per second for a point at the instant of contact with the rail?

6. A locomotive driving wheel 2 m. in diameter makes 200 revolutions per minute; what is the instantaneous centripetal acceleration for the highest point of the wheel? (Note. The radius of rotation for the highest point is at that instant 2 m.)

CHAPTER V

MECHANICS OF SOLIDS

MEASUREMENT OF FORCE

98. Force. — The effects of force in producing motion are among our commonest experiences. We drop a knife and it falls by the force of gravity; a mountain stream rushes downward by reason of the same mysterious force; the leaves of the trees rustle in the breeze, the branches sway violently in the wind, and their trunks are even twisted off by the force of the tornado; powder explodes in a rifle and the bullet speeds to its mark; loud thunder shakes the ground and vivid lightning rends a tree or shatters a flagstaff. From such familiar facts is derived the conception that *force is anything that produces motion or change of motion* in material bodies.

99. Units of Force. — Two systems of measuring force in common use are the *gravitational* and the *absolute*. The gravitational unit of force is the *weight* of a standard mass, such as the *pound of force*, the *gram of force*, or the *kilogram of force*. A pound of force means one equal to the force required to lift the mass of a pound against the downward pull of gravity. The same is true of the metric units with the difference in the mass lifted.

Gravitational units of force are not strictly constant because the weight of the same mass varies from point to point on the earth's surface, and at different elevations. The actual force necessary to lift the mass of a pound at

the poles of the earth is greater than at the equator; it is less on the top of a high mountain than in the neighboring valleys, and still less than at the level of the sea. Gravitational units of force are convenient for the common purposes of life and for the work of the engineer, but they are not suitable for precise measurements.

The so-called "absolute" unit of force in the *c.g.s.* system is the *dyne* (from the Greek word meaning *force*). *The dyne is the force which imparts to a gram mass an acceleration equal to one centimeter per second per second.* This unit is invariable in value, for it is independent of the variable force of gravitation. It is indispensable in framing the definitions of modern electrical and magnetic units.

100. Relation between the Gram of Force and the Dyne. — The *gram of force* is the pull of the earth on a mass of one gram (the place on the earth's surface is not specified). Since the attraction of the earth in New York imparts to a gram mass an acceleration of 980 cm. per second per second, while the *dyne* produces an acceleration of only 1 cm. per second per second, it follows that the gram of force in New York is equal to 980 dynes, or the dyne is $\frac{1}{980}$ of the gram of force. The pull of gravity on a gram mass in other latitudes is not exactly the same as in New York, but for the purposes of this book it will be sufficiently accurate to say that *a gram of force is equal to* 980 *dynes.* It will be seen, therefore, that the value of any force expressed in dynes is approximately 980 times as great as in grams of force. Conversely, to convert dynes into grams of force, divide by 980.

101. How a Force is Measured. — The simplest device for measuring a force is the spring balance (Fig. 84). The

common draw scale is a spring balance graduated in pounds and fractions of a pound. If a weight of 15 lb., for example, be hung on the spring and the position of the pointer be marked, then any other 15 lb. of force will stretch the spring to the same extent in any direction. If a man by pulling in any direction stretches a spring 3 in., and if a weight of 150 pounds also stretches the spring 3 in. the force exerted by the man is 150 pounds of force.

Fig. 84

The spring balance may be graduated in pounds of force, kilograms or grams of force, or in dynes. If correctly graduated in dynes, it will give right readings at any latitude or elevation.

102. Graphic Representation of a Force. — A force has not only *magnitude* but also *direction*; in addition, it is often necessary to know its *point of application*. These three particulars may be represented by a straight line drawn through the point of application of the force in the direction in which the force acts, and as many units in length as there are units of force, or some multiple or submultiple of that number. If a line 1 cm. long stands for a force of 15 dynes, a line 4 cm. long, in the direction AB (Fig. 85), will represent a force of 60 dynes acting in the direction from A to B. Any point on the line AB may be used to indicate the point at which the force is applied.

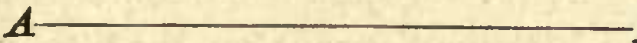


Fig. 85

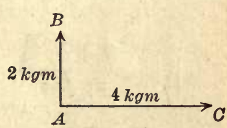


Fig. 86

If it is desired to represent graphically the fact that two forces act on a body at the same time, for example, 4 kgm. of force horizontally and 2 kgm.

of force vertically, two lines are drawn from the point of application A (Fig. 86), one 2 cm. long to the right, and the other 1 cm. long toward the top of the page. The lines AB and AC represent the forces in point of application, direction, and magnitude, on a scale of 2 kgm. of force to the centimeter.

II. COMPOSITION OF FORCES AND OF VELOCITIES

103. Composition of Forces. — The *resultant* of two or more forces is a single force which will produce the same effect on the motion of a body as the several forces acting together. (Note the exception in the case of a couple, § 106.) *The process of finding the resultant of two or more forces is known as the composition of forces.* It will be convenient to consider first the composition of parallel forces, and then that of forces acting at an angle.

104. The Resultant of Parallel Forces. — Suspend two draw scales, A and B (Fig. 87), from a suitable support by cords. Attach to them a graduated bar supporting the weight W. Adjust the draw scales and the attached cords so that they are all vertical. Read the scales and note the distances CE and ED; also compare the value of W with the sum of the readings of A and B. Change the position of the point E and repeat the observations. It will be found in each case that $\frac{A}{B}=\frac{ED}{CE}\cdot$ Hence the following principle:

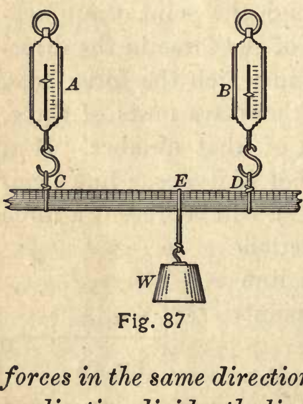


Fig. 87

The resultant of two parallel forces in the same direction is equal to their sum; its point of application divides the line joining the points of application of the two forces into two parts which are inversely as the forces.

105. Equilibrium. — It will be apparent that the weight W is equal and opposite to the resultant of the two forces measured by the draw scales A and B (Fig. 87). The three forces produce neither motion nor change of motion and are said to be in *equilibrium;* each of the forces is equal and opposite to the resultant of the other two and is called their *equilibrant.* The equilibrium of a body does not mean that its velocity is zero, but that its acceleration is zero. ***Rest means zero velocity; equilibrium, zero acceleration.***

106. Parallel Forces in Opposite Directions. — If two parallel forces, as A and W (Fig. 87), act in opposite directions, their resultant is their difference (equal and opposite to the force B), and it acts in the direction of the larger force (in this case downward in the same direction as W).

When the two parallel forces acting in opposite directions are *equal*, they form a *couple.* The resultant of a couple is zero; that is, no single force can be substituted for it and produce the same effect. A couple produces motion of rotation only, in which all the particles of the body to which it is applied rotate in circles about a common axis. For example, a magnetized sewing needle floated on water is acted on by a couple when it is displaced from a north-and-south position. One end of the needle is attracted toward the north, and the other toward the south, with equal and parallel forces. The effect is to rotate the needle about a vertical axis until it returns to a north-and-south position. The common auger, as a carpenter employs it to bore a hole, illustrates a couple in the equal and opposite parallel forces applied by the two hands.

107. The Resultant of Two Forces Acting at an Angle. — Tie together three cords at D (Fig. 88) and fasten the three ends to the hooks of the draw scales A, B, C. Pass their rings over pegs set in a board at such distances apart that the draw scales will all be stretched. Record the readings of the scales, and by means of a protractor (see Appendix I) measure the angles formed at D by the cords. Draw on a sheet of paper three lines meeting at a point D, and forming with one another these angles. Lay off on the three

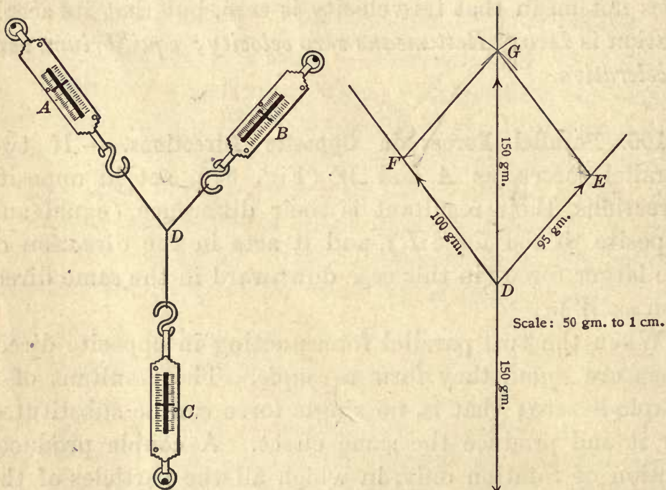


Fig. 88

lines, on some convenient scale, distances to represent the readings of the draw scales, DF for A, DE for B, and DC for C. With DF and DE as adjacent sides, complete the parallelogram $DFGE$ and draw the diagonal DG. DG is the resultant of the forces A and B, and its length on the scale chosen will be found equal to that of DC, their equilibrant. Here again, each force is equal and opposite to the resultant of the other two.

When two forces act together on a body at an angle, the resultant lies between the two; its position and value may be found by applying the following principle, known as the *parallelogram of forces:*

If two forces are represented by two adjacent sides (DF and DE) of a parallelogram, their resultant is represented by the diagonal (DG) of the parallelogram drawn through their common point of application (D).

When the two forces are equal, their resultant by the principle of symmetry lies midway between them. If the two forces are at right angles (Fig. 89), the parallelogram becomes a rectangle and the two forces and their resultant are represented by the three sides of a right triangle, *AB*, *BD*, *AD*. The value of the resultant in this case may be found by computing the hypotenuse of the triangle.

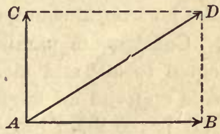


Fig. 89

For example, if the forces at right angles are 6 kgm. of force and 8 kgm. of force, their resultant is

$$\sqrt{6^2 + 8^2} = 10 \text{ kgm. of force.}$$

108. Component of a Force in a Given Direction. — It frequently occurs that if a force produces any motion, it must be in a direction other than that of the force itself.

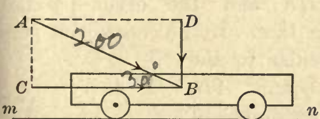


Fig. 90

For example, suppose the force *AB* (Fig. 90) applied to cause a car to move along the rails *mn*. The force *AB* evidently produces two effects; it tends to move the car along the rails, and it increases the pressure on them. The two effects are produced by the two forces *CB* and *DB* respectively. They are therefore the equivalent of *AB*. The force *CB* is called the component of *AB* in the direction of the rails *mn*, and *DB* is the component perpendicular to them. *The component of a force in a given direction is its effective value in this direction.*

To find the component in a given direction, construct on

the line representing the force, as the diagonal, a rectangle, the sides of which are respectively parallel and perpendicular to the direction of the required component; the length of the side parallel to the given direction represents the component sought.

EXAMPLE. Let a force of 200 lb. be applied to a truck, as AB in Fig. 90; and let it act at an angle of 30° with the horizontal. Find the horizontal component pushing the truck forward.

Construct a parallelogram (see Appendix) with the angle ABC equal to 30° and measure the side CB. Or, remembering that the side opposite an angle of 30° is half the hypotenuse, it follows that AC is 100 lb. of force, and the third side of the right triangle is then

$$CB = \sqrt{200^2 - 100^2} = 173.2 \text{ lb. of force.}$$

The kite and the sailboat are two familiar illustrations of the principle. In the case of the kite, the forces acting are the weight of the kite AB (Fig. 91), the pull of the string AC, and the force of the wind. The force of the wind may be resolved into two components, one perpendicular to the face of the kite HK, and the other parallel to the face. If the component perpendicular to the face equals AD, the resultant of AB and AC, then the kite will be at rest; if greater, then the kite will move upward; if less, the kite will descend.

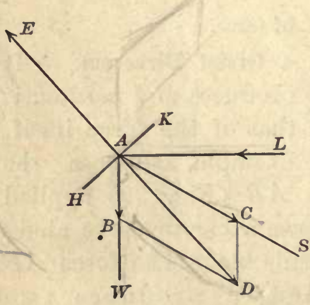


Fig. 91

In the case of the sailboat, the sail is set at such an angle that the wind strikes the rear face. In Fig. 92, BS represents the sail, and AB the direction and force of the wind. This force may be resolved into two rectangular components, CB and DB, of which CB represents the intensity of the force that drives the boat forward.

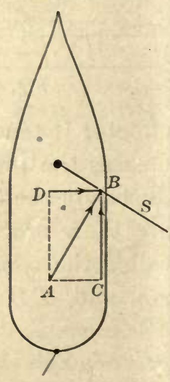


Fig. 92

109. Composition and Resolution of Velocities. — At the Paris exposition in 1900 a continuous moving sidewalk carried visitors around the grounds. A person walking on this platform had a velocity with respect to the ground made up of the velocity of the sidewalk relative to the ground and the velocity of the person relative to the moving walk. The several velocities entering the result are the *component velocities.* Velocities may be combined and resolved by the same methods as those applying to forces. When several motions are given to a body at the same time, its actual motion is a compromise between them, and the compromise path is the resultant.

The following is an example of the composition of two velocities at right angles: A boat can be rowed in still water at the rate of 5 mi. an hour; what will be its actual velocity if it be rowed 5 mi. an hour across a stream running 3 mi. an hour?

Let AB (Fig. 93) represent in length and direction the velocity of 5 mi. an hour across the stream, and AC, at right angles to AB, the velocity of the current, 3 mi. an hour, both on the same scale. Complete the parallelogram $ABDC$, and draw the diagonal AD through the point A common to the two component velocities. AD represents the actual velocity of the boat; its length on the same scale as that of the other lines is 5.83. The resultant velocity is therefore 5.83 miles an hour in the direction AD.

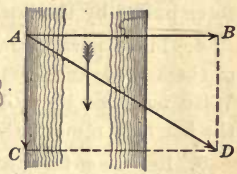


Fig. 93

When the angle between the components is a right angle, as in the present case, the diagonal AD is the hypotenuse of the right triangle ABD. Its square is therefore the sum of the squares of 5 and 3, or

$$AD = \sqrt{5^2 + 3^2} = 5.83.$$

When the angle at A is not a right angle, the approximate resultant may be found by a graphic process of measurement.

A velocity, like a force, has both direction and magni-

tude, and a component of it in any given direction may be found in precisely the same way as in the case of a force, § 108.

Problems

NOTE. Solve graphically the problems involving forces or velocities at an angle. Consult Appendix I for methods of drawing.

1. A body is acted on by two parallel forces of 20 and 30 lb. of force in the same direction; their points of application are 60 in. apart. Find the value of the resultant and the distance of its point of application from either force.

SUGGESTION. Let x be the distance of the point of application of the resultant from that of the force 20. Then $60 - x$ is its distance from the point of application of the force 30, and by §104, $\frac{20}{30} = \frac{60 - x}{x}$.

2. A weight of 210 lb. is carried at the middle of a bar 6 ft. long by a boy at one end and a man at the other side of the middle. Where must the man take hold so that he shall carry twice as much as the boy?

3. A horse and a colt are hitched side by side to a loaded wagon. At what point of the double tree must it be attached to the tongue of the wagon so that the colt will pull two pounds to three pounds of force pulled by the horse, the double tree being 40 in. long?

4. Three parallel forces are acting on a bar 104 cm. long. Two of them, 500 and 800 dynes respectively, are applied at the ends. What must be the third force and where must it be applied so that the bar may remain at rest and the three forces be in equilibrium?

5. Resolve a force of 100 dynes into two parallel forces with their points of application 20 and 30 cm., respectively, from that of the original force.

6. Two parallel forces of 100 and 150 dynes, respectively, have their points of application 50 cm. apart. What third parallel force will produce equilibrium, and where must it be applied so that the three points of application are in the same straight line?

7. Two forces, 30 and 40 grams of force, act at an angle of 60°. Find the resultant.

8. A train is running with a speed of 30 mi. an hour. A package is thrown perpendicularly from it with a velocity of 20 ft. a second. What is the velocity of the package with respect to the ground?

9. A sailboat is going eastward, the wind is from the northwest, and the sail is set at an angle of 30° with the direction of the wind. If the wind is blowing 12 mi. an hour, what is its component perpendicular to the sail?

10. A mass of 30 gm. is suspended by a string. It is pulled aside by a horizontal force of 17.32 gm. of force, and the string then makes an angle of 30° with the vertical (Fig. 94). Find the tension in the string. (Note that in a right triangle with a 30° angle, the side opposite this angle is half the hypotenuse.)

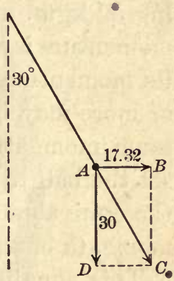


Fig. 94

11. Horses attached to a car pull at an angle of 30° with the track and with a force of 1200 lb. What is the force moving the car?

12. A cord supporting a picture weighing 15 lb. passes over a knob so that the angle between the two parts of the cord is 60°. What is the tension in the cord?

III. NEWTON'S LAWS OF MOTION

110. Momentum. — So far we have considered motion without reference to the mass moved, and without considering the relation between force on the one hand and the moving mass and its velocity on the other. Before taking up the laws of motion, which outline the relations between force and motion, it is necessary to define two terms intimately associated with these laws. The first of these is *momentum*. *Momentum is the product of the mass and the linear velocity* of a moving body.

$$\textit{Momentum} = \textit{mass} \times \textit{velocity}, \text{ or } M = mv. \qquad \text{(Equation 8)}$$

In the *c.g.s.* system, the unit of momentum is the momentum of a mass of 1 gm. moving with a velocity of 1 cm. per second. It has no recognized name. In the English system, the unit of momentum is the momentum of a mass of 1 lb. moving with a velocity of 1 ft. per second.

111. Impulse. — Suppose a ball of 10 gm. mass to be fired from a rifle with a velocity of 50,000 cm. per second. Its momentum would be 500,000 units. If a truck weighing 50 kgm. moves at the rate of 10 cm. per second, its momentum is also 500,000 units. But the ball has acquired its momentum in a fraction of a second, while a minute or more may have been spent in giving to the truck the same momentum. In some sense the effort required to set the ball in motion is the same as that required to give the equivalent amount of motion to the truck, because the momenta of the two are equal.

This equality is expressed by saying that the *impulse* is the same in the two cases. Since the effect is doubled if the value of the force is doubled, or if the time during which the force continues to act is doubled, it follows that *impulse is the product of the force and the time it continues to act.* In estimating the effect of a force, the time element and the magnitude of the force are equally important. The term *impulse* takes both into account.

112. The Laws of Motion. —The laws of motion, first enunciated by Sir Isaac Newton, are to be regarded as physical axioms, incapable of rigorous experimental proof. They must be considered as resting on convictions drawn from observations and experiment in the domain of physics and astronomy. The results derived from their application have so far been found to be invariably true. They may be stated as follows:

I. *Every body continues in its state of rest or of uniform motion in a straight line, except in so far as it may be compelled by applied force to change that state.*

II. *Change of momentum is proportional to the impulse which produces it, and takes place in the direction in which the force acts.*

Sir Isaac Newton (1642–1727) is celebrated for his discoveries in mathematics and physics. He was a Fellow of Trinity College, Cambridge. He discovered the binomial theorem in algebra and laid the foundation of the calculus. His greatest work is the *Principia*, a treatise on motion and the laws governing it. His greatest discoveries are the laws of gravitation and the composition of white light.

From Kepler's laws of the planetary orbits Newton proved that the attraction of the sun on the planets varies inversely as the squares of their distances.

He was also distinguished in public life. He sat in Parliament for the University of Cambridge, was at one time Master of the Mint, and the reformation of the English coinage was largely his work.

III. *To every action there is always an equal and contrary reaction; or the mutual actions of two bodies are always equal and oppositely directed.*

113. Discussion of the First Law. — This law is known as the *law of inertia* (§ 7), since it asserts that a body persists in its condition of either rest or uniform motion, unless it is compelled to change that state by the action of an external force. It is further true that a body offers resistance to any such change in proportion to its *mass*. Hence the term *mass* is now commonly used to denote the measure of the body's inertia (§ 9).

From this law we also derive the Newtonian definition of force, for the law asserts that *force is the sole cause of change of motion.*

114. Discussion of the Second Law. — The first law teaches that a change of motion is due to impressed force. The second law points out, in the first place, what the measure of a force is. It was restated by Maxwell as follows: "*The change of momentum of a body is numerically equal to the impulse which produces it, and is in the same direction,*" or

momentum (mass × velocity) = *impulse* (force × time).

Expressed in symbols, $mv = ft$. . . . (Equation 9)

Hence, $f = \frac{mv}{t}$.

The initial velocity of the mass m before the force f acted on it is here assumed to be zero, and v is the velocity attained in t seconds. Then the total momentum imparted in the time t is mv, and therefore $\frac{mv}{t}$ is *the rate of change of momentum. Force is therefore measured by the rate of change of momentum.* Since $\frac{v}{t}$ is the rate of change

of velocity, or the acceleration a (see equation 5), we may write

$$f = ma. \quad . \quad . \quad . \quad \text{(Equation 10)}$$

We see from this that *force may also be measured by the product of the mass moved and the acceleration imparted to it.* Therefore when the mass m is unity, the force is numerically equal to the acceleration it produces. Hence the definition of the *dyne* (§ 99).

This law teaches, in the second place, that *the change of momentum is always in the direction in which the force acts.* Hence, when two or more forces act together, each produces its change of momentum independently of the others and in its own direction. This principle lies at the foundation of the method of finding the resultant effect of two forces acting on a body in different directions (§ 107).

On a horizontal shelf about two meters above the floor are placed two marbles, one on each side of a straight spring fixed vertically over a hole in the shelf. One marble rests on the shelf and the other is held over the hole between the spring and a block fixed to the shelf (Fig. 95). When the hammer falls and strikes the spring, it projects the one marble horizontally and lets the other one fall vertically. The two reach the floor at the same instant. Both marbles have the same vertical acceleration.

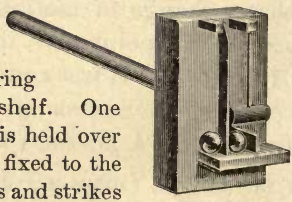


Fig. 95

115. Discussion of the Third Law. — The essence of this law is that all action between two bodies is *mutual.* Such action is known as a *stress* and a stress is always a two-sided phenomenon, including both *action* and *reaction.* The third law teaches that these two aspects of a stress are always equal and in opposite directions. The stress in a stretched elastic cord pulls the two bodies to which it is attached equally in opposite directions; the stress in a

compressed rubber buffer or spring exerts an equal push both ways; the former is called a *tension* and the latter a *pressure*.

ILLUSTRATIONS. The tension in a rope supporting a weight is a stress tending to part it by pulling adjacent portions in opposite directions. The same is obviously true if two men pull at the ends of the rope. An ocean steamship is pushed along by the reaction of the water against the blades of the propeller. The same is true of an aëroplane, only in this case the reaction against the blades is by the air, and the blades are longer and revolve much faster than in water in order to move enough air to furnish the necessary reaction. When a man jumps from a rowboat to the shore, he thrusts the boat backwards. An athlete would not make a record standing jump from a feather bed or a spring board. When a ball is shot from a gun, the gun recoils or "kicks." All attraction, such as that between a magnet and a piece of iron, is a stress, the magnet attracting the iron and the iron the magnet with the same force.

Practical use is made of reaction to turn the oscillating electric fan from side to side so as to blow the air in different directions. A rectangular sheet of brass is bent lengthwise at right angles and is pivoted so as to turn 90° about a vertical axis (Fig. 96). When one half of this bent sheet is exposed to the air current, the reaction sustained by the blades of the fan on this side is in part balanced by the reaction of the bent sheet; but on the opposite half of the fan the reaction of the blades is not balanced. Hence the whole fan turns about a vertical axis on the standard until a lever touches a stop and shifts the bent strip so as to expose the other half of it to the air current from the opposite half of the fan. The fan then reverses its slow motion and turns to the other side.

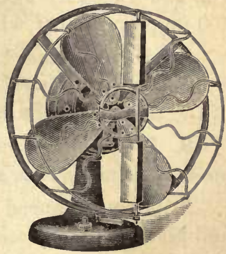


Fig. 96

Since force is measured by the rate at which momentum changes, the third law of motion is equivalent to the following:

In every action between two bodies, the momentum

gained by the one is equal to that lost by the other, or the momenta in opposite directions are the same.

Problems

1. Why will not the same impulse impart to a 2-lb. ball the same velocity as it does to a 1-lb. ball?

2. What is the momentum of a mass of 250 gm. moving with a velocity of 75 cm. per second?

3. Calculate the ratio of the momentum of a ball whose mass is 5 lb. and speed 1500 ft. per second to that of a 50-lb. ball moving with a speed of 1800 ft. per minute.

4. What velocity must be given to a mass of 25 kgm. that it may have the same momentum as a 75-kgm. ball moving with a velocity of 1500 cm. per second?

5. A 10-lb. gun is loaded with a half-ounce ball. When fired the ball has a velocity of 1800 ft. per second. What is the velocity of recoil of the gun?

6. Two balls have equal momenta. The first has a mass of 200 gm. and a velocity of 20 m. per second; the second has a velocity of 600 m. per minute; what is its mass?

7. An unbalanced force acts on a mass of 100 gm. for 5 seconds, and imparts to it a velocity of 2.5 cm. per second. What is the value of the force in dynes (§ 99)?

8. What is the acceleration when a force of 50 dynes acts on a mass of 8 gm.? How far will the mass of 8 gm. move in 4 sec.?

9. An unbalanced force of 60 dynes acts on a body for 1 min. and gives to it a velocity of 1200 cm. per second. What is the mass of the body?

10. Two grams of force act continuously on a mass of 49 gm. for 10 seconds. Find the velocity acquired and the space traversed. (To apply equations (9) and (10) the force must be expressed in dynes.)

IV. GRAVITATION

116. Weight. — *The attraction of the earth for all bodies is called gravity.* The *weight* of a body is the measure of this

attraction. It is a pull on the body and therefore a force. It makes a body fall with uniform acceleration called the *acceleration of gravity* and denoted by g. If we represent the weight of a body by w and its mass by m, by equation (10), $w = mg$. From this it appears that *the weight of a body is proportional to its mass*, and that *the ratio of the weights of two bodies at any place is the same as that of their masses.* Hence, in the process of weighing with a beam balance, the mass of the body weighed is compared with that of a standard mass. When a beam balance shows equality of weights, it shows also equality of masses.

Fig. 97

117. Direction of Gravity. — The direction in which the force of gravity acts at any point is very nearly toward the earth's center. It may be determined by suspending a weight by a cord passing through the point. The cord is called a *plumb line* (Fig. 97), and its direction is a *vertical line.* A plane or line perpendicular to a plumb line is said to be *horizontal.* Vertical lines drawn through neighboring points may be considered parallel without sensible error.

118. Center of Gravity. — A body is conceived to be composed of an indefinitely large number of particles, each of which is acted on by gravity. For bodies of ordinary size, these forces of gravity are parallel and proportional to the masses of the several small parts. *The point of application of their resultant is the center of gravity of the body.*

If the body is uniform throughout, the position of its

center of gravity depends on its geometrical figure only. Thus, the center of gravity (1) of a straight rod is its middle point; (2) of a circle or ring, its center; (3) of a sphere or a spherical shell, its center; (4) of a parallelogram, the intersection of its diagonals; (5) of a cylinder or a cylindrical pipe, the middle point of its axis.

It is necessary to guard against the idea that the force of gravity on a body acts at its center of gravity. Gravity acts on all the particles composing the body, but its effect is generally the same as if the resultant, that is, the weight of the body, acted at its center of gravity. It will be seen from the examples of the ring and the cylindrical pipe that the center of gravity may lie entirely outside the body.

119. Law of Universal Gravitation. — It had occurred to Galileo and other early philosophers that the attraction of gravity extends beyond the earth's surface, but it remained for Sir Isaac Newton to discover the law of universal gravitation. He derived this great generalization from a study of the planetary motions discovered by Kepler. The law may be expressed as follows:

Every portion of matter in the universe attracts every other portion, and the stress between them is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

For spherical bodies, like the sun, the earth, and the planets, the attraction of gravitation is the same as if all the matter in them were concentrated at their centers; hence, in applying to them the law of gravitation, the distance between them is the distance between their centers. Calculations made to find the centripetal acceleration of the moon in its orbit show that it is attracted to the earth

with a force which follows the law of universal gravitation.[1]

120. Variation of Weight. — Since the earth is flattened at the poles, it follows from the law of gravitation that the acceleration of gravity, and the weight of any body, increase in going from the equator toward the poles. If the earth were a uniform sphere and stationary, the value of g would be the same all over its surface. But the value of g varies from point to point on the earth's surface, even at sea level, both because the earth is not a sphere and because it rotates on its axis. The centripetal acceleration of a point at the equator, owing to the earth's rotation on its axis, is $\frac{1}{289}$ the acceleration of gravity g. Since 289 is the square of 17, and the centripetal acceleration varies as the square of the velocity (§95), it follows that if the earth were to rotate in one seventeenth of a day, that is, 17 times as fast as it now rotates, the apparent value of g at the equator would become zero, and bodies there would lose all their weight.

The value of g at the equator is 978.1 and at the poles 983.1, both in centimeters per second per second. At New York it is 980.15 centimeters, or 32.16 feet, per second per second.

121. Equilibrium under Gravity. — When a body rests on a horizontal plane, its weight is equal and opposite to the reaction of the plane. The vertical line through its center of gravity must therefore fall within its base of support. If this vertical line falls outside the base, the weight of the body and the reaction of the plane form a couple (§ 106), and the body overturns.

The three kinds of equilibrium are, (1) *stable*, for any displacement which causes the center of gravity to rise;

[1] Carhart's *College Physics*, § 58.

(2) *unstable*, for any displacement which causes the center of gravity to fall; (3) *neutral*, for any displacement which does not change the height of the center of gravity.

Fill a round-bottomed Florence flask one quarter full of shot and cover them with melted paraffin to keep them in place (Fig. 98). Tip the flask over; after a few oscillations it will return to an upright position. Repeat the experiment with a similar empty flask; it will not stand up, but will rest in any position on its side and with the top on the table. The loaded flask cannot be tilted over without raising its center of gravity; in a vertical position it is therefore stable and when tipped over, unstable, for it returns to a vertical position. For the empty flask, its center of gravity is lower when it lies on its side than when it is erect. Rolling it around does not change the height of its center of gravity and its equilibrium is thus neutral.

Fig. 98

The three funnels of Fig. 99 illustrate the three kinds of equilibrium on a plane.

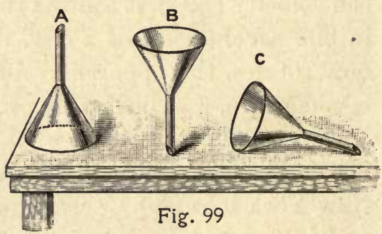


Fig. 99

A rocking horse, a rocking chair, and a half sphere resting on its convex side are examples of stable equilibrium. An egg lying on its side is in neutral equilibrium for rolling and stable equilibrium for rocking; it is unstable on either end. A lead pencil supported on its point is in unstable equilibrium. Any such body may become stable by attaching weights to it in such a manner as to lower the center of gravity below the supporting point (Fig. 100).

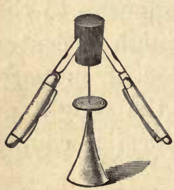


Fig. 100

122. Stability. — *Stability is the state of being firm or stable.* The higher the center of gravity of a body must be

lifted to put the body in unstable equilibrium or to overturn it, the greater is its stability. This condition is met by a relatively large base and a low center of gravity. A pyramid is a very stable form. On account of the large area lying within the four feet of a quadruped, its stability is greater than that of a biped. A child is therefore able to creep "on all fours" before it learns to maintain stable equilibrium in walking. A boy on stilts has smaller stability than on his feet because his support is smaller and his center of gravity higher.

Stability may be well illustrated by means of a brick. It has greater stability when lying on its narrow side (2″ × 8″) than when standing on end; and on its broad side (4″ × 8″) its stability is still greater. Let Fig. 101 represent a brick lying on its narrow side in *A* and standing on end in *B*. In both cases to overturn it its center of gravity *c* is lifted to the same height, but the vertical distance *bd* through which the center of gravity must be lifted is greater in *A* than in *B*.

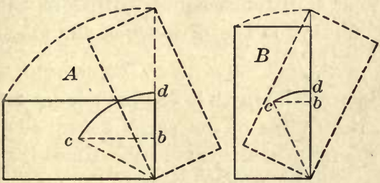


Fig. 101

A tall chimney or tower has no great stability because its base is relatively small and its center of gravity high. A high brick wall is able to support a great crushing weight, but its stability is small unless it is held by lateral walls and floor beams.

Questions and Problems

1. If one jumps off the top of an empty barrel standing on end, why is one likely to get a fall?

2. Where is the center of gravity of a knife supported as in Fig. 102?

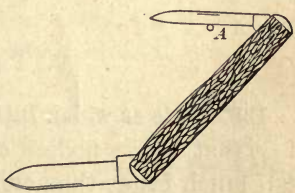


Fig. 102

3. Can you devise a method of finding where the center of gravity of a uniform triangle is?

4. Show by a figure why a ball rolls down hill the faster, the steeper the hill.

5. Why are low wagons better adapted for use on hillsides than high ones?

6. If a body at the equator weighs 9781 gm. *on a spring balance*, what would it weigh at the north pole? (Weight is proportional to g.)

7. If a body weighs 16 kgm. at sea level *on a spring balance*, how many grams less will it weigh on the top of a mountain 2 mi. above sea level, if the radius of the earth is 4000 mi.? (The value of g is inversely as the square of the distance from the center of the earth.)

8. If the acceleration of gravity g is 32.2 ft. per second per second on the earth's surface, what is it at a distance equal to that of the moon, if the earth's radius is 4000 mi. and the distance of the moon 240,000 mi.?

9. If the acceleration of gravity on the earth is 980 cm. per second per second, what is it on Mars, the radius of the earth being 4000 mi., that of Mars 2000 mi., and the mass of the earth nine times that of Mars? (The accelerations are directly proportional to the masses and inversely proportional to the squares of the radii.)

10. If a body weighs 45 lb. *on a spring balance* on the earth, what would it weigh on Mars, the radius of the earth being 4000 mi., that of Mars 2000 mi., and the mass of the earth nine times that of Mars?

11. How far above the earth's surface would a pound ball have to be taken to reduce its weight to 1 oz., if the earth's radius is 4000 mi.?

V. FALLING BODIES

123. Rate at which Different Bodies Fall. — It is a familiar fact that heavy bodies, such as a stone or a piece of iron, fall much faster than such light bodies as feathers, bits of paper, and snow crystals. Before the time of Galileo it was supposed that different bodies fall with velocities pro-

portional to their weights. This erroneous notion was corrected by Galileo by means of his famous experiment of dropping various bodies from the top of the leaning tower of Pisa (Fig. 103) in the presence of professors and students of the university in that city. He showed that bodies of different materials fell from the top of the tower to the ground, a height of 180 feet, in practically the same time; also that light bodies, such as paper, fell with velocities approaching more and more nearly those of heavy bodies the more compactly they were rolled together in a ball. The slight differences in the velocities observed he rightly ascribed to the resistance of the air, which is relatively greater for light bodies than for heavy compact ones. This inference Galileo could not completely verify because the air pump had not yet been invented.

Fig. 103

124. Resistance of the Air. — Place a small coin and a feather, or a shot and a bit of tissue paper, in a glass tube from 4 to 6 feet long. It is closed at one end and fitted with a stopcock at the other (Fig. 104). Hold the tube in a vertical position and suddenly invert it; the coin or the shot will fall to the bottom first. Now exhaust the air as perfectly as possible; again invert the tube quickly; the lighter

body will now fall as fast as the heavier one. This experiment, known as the "Guinea and Feather Tube," was first performed by Newton. It demonstrates that if the resistance of the air were wholly removed, all bodies at the same place would fall with the same acceleration.

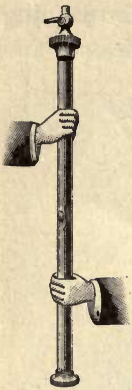


Fig. 104

An interesting modification of the Newtonian experiment is the following: Cut a round piece of paper slightly smaller than a cent and drop the cent and the paper side by side; the cent will reach the floor first. Then lay the paper *on the cent* and drop them in that position; the paper will now fall as fast as the cent. Explain.

The friction of the air against the surface of bodies moving through it limits their velocity. A cloud floats, not because it is lighter than the atmosphere, for it is actually heavier, but because the surface friction is so large in comparison with the weight of the minute drops of water, that the limiting velocity of fall is very small.

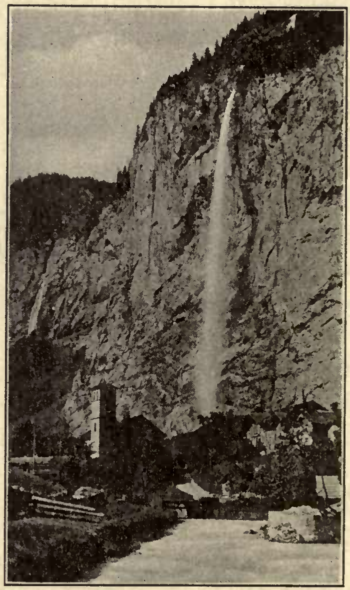


Fig. 105

When a stream of water flows over a high precipice, it is broken into fine spray and falls slowly. Such is the explanation of the Staubbach fall (dust brook) at Lauterbrunnen in Switzerland (Fig. 105). The precipice is 300 m. high, and the fall viewed from its face resembles a magnificent transparent veil, kept in movement by currents of air.

125. Laws of Falling Bodies. — Galileo verified the following laws of falling bodies: —

I. *The velocity attained by a falling body is proportional to the time of falling.*

II. *The distance fallen is proportional to the square of the time of descent.*

III. *The acceleration is twice the distance a body falls in the first second.*

These laws will be recognized as identical with those derived for uniformly accelerated motion, §§ 91 and 92. If the inclined plane in Galileo's experiment be tilted up steeper, the effect will be to increase the acceleration down the plane; and if the board be raised to a vertical position, the marble will fall freely under gravity and the acceleration will become g (§ 120).

Since the acceleration g is sensibly constant for small distances above the earth's surface, the equations already obtained for uniformly accelerated motion may be applied directly to falling bodies, by substituting g for a in equations (5) and (6). Thus we have

$$v = gt, \quad . \quad . \quad . \quad \text{(Equation 11)}$$

and

$$s = \tfrac{1}{2} gt^2. \quad . \quad . \quad \text{(Equation 12)}$$

If in equation (12) t is one second, $s = \frac{1}{2} g$; or the distance a body falls from rest in the first second is half the acceleration of gravity. A body falls 490 cm. or 16.08 ft. the first second; and the velocity attained is 980 cm. or 32.16 ft. per second.

126. Projection Upward. — When a body is thrown vertically upward, the acceleration is negative, and it loses each second g units of velocity (980 cm. or 32.16 ft.). Hence, the time of ascent to the highest point is the time taken to bring the body to rest. If the velocity lost is g units a second, the time required to lose v units of velocity will be

the quotient of v by g, or

$$\textit{time of ascent} = \frac{\textit{velocity of projection upward}}{\textit{acceleration of gravity}}.$$

In symbols $$t = \frac{v}{g} \quad . \quad . \quad . \quad . \quad \text{(Equation 13)}$$

For example, if the velocity of projection upward were 1470 cm. per second, the time of ascent, neglecting the frictional resistance of the air, would be $\frac{1470}{980}$, or 1.5 seconds. This is the same as the time of descent again to the starting point; hence, *the body will return to the starting point with a velocity equal to the velocity of projection but in the opposite direction.* In this discussion of projection upward, the resistance of the air is neglected.

Problems

In the following problems, unless otherwise stated in the problem, g is to be taken as 980 cm. or 32 ft. per second per second.

1. A brick falls to the ground from the top of a chimney 64 ft. high. What will be the time of descent, and with what velocity will it strike the ground? (Use equation (12) for the time, and equation (11) for the velocity.)

2. A stone dropped from a bridge strikes the water in 3 sec. after leaving the hand. Find the height of the bridge above the water.

3. If a stone thrown vertically upward returns to the ground in 4 sec., how high does it ascend?

4. A ball is thrown over a tree 100 ft. high. How long before it will return to the ground?

5. A ball fired horizontally reaches the ground in 4 sec. What was the height of the point from which it was fired (§ 114)?

6. A cannon ball is fired horizontally from a fort at an elevation of 78.4 m. above the level of the neighboring sea. How many seconds before it will strike the water?

7. An iron ball was dropped from an aëroplane moving eastward at the rate of 45 mi. an hour. It reached the ground 528 ft. east of

the vertical line through the point at which it was dropped. What was the elevation of the aëroplane?

8. With what velocity must a ball be fired upward to rise to the height of the Washington Monument, 555 ft., and how long will it be in the air?

9. An inclined plane 40 ft. long is elevated at one end 2 ft. In what time will a ball roll down it, neglecting all resistance? (The acceleration down the plane is the component of g parallel to the incline.)

10. A body slides without friction down an inclined plane 300 cm. long and 24.5 cm. high. If it moves 40 cm. during the first second, what is the computed value of g?

VI. CENTRIPETAL AND CENTRIFUGAL FORCE

127. Definition of Centripetal and Centrifugal Force. — Attach a ball to a cord and whirl it around by the hand. The ball pulls on the cord, the pull increasing with the velocity of the ball. If the ball is replaced by a heavier one, with the same velocity the pull is greater. If a longer cord is used, the pull is less for the same velocity in the circle.

The constant pull which deflects the body from a rectilinear path and compels it to move in a curvilinear one is the centripetal force. The resistance which a body offers, on account of its inertia, to deflection from a straight line is the centrifugal force. When the motion is uniform and circular, the force is at right angles to the path of the body around the circle and constant.

These two forces are the two aspects of the stress in the cord (third law of motion), the action of the hand on the ball, and the reaction of the ball on the hand.

128. Value of Either Force. — The centripetal acceleration for uniform circular motion (§ 95) is $a = \frac{v^2}{r}$, where v

is the uniform velocity in the circle, and r is the radius. Further, in § 114 the relation between force and acceleration was found to be, force equals the product of the mass and the acceleration imparted to it by the force. Hence we have

centripetal force = *mass* × *centripetal acceleration*,

or $$f = \frac{mv^2}{r}. \quad . \quad . \quad . \quad \text{(Equation 14)}$$

This relation gives the value of either the centripetal or the equal centrifugal force in the absolute system of measurement, because it is derived from the laws of motion and is independent of gravity. In the metric system m must be in grams, v in centimeters per second, and r in centimeters; f is then in dynes. To obtain f in grams of force, divide by 980 (§ 100). In the English system, m must be in pounds, v in feet per second, and r in feet; dividing by 32.2, the result will be in pounds of force.

For example: If a mass of 200 gm. is attached to a cord 1 m. long and is made to revolve with a velocity of 140 cm. per second, the tension in the cord is $\frac{200 \times 140^2}{100} = 39{,}200$ dynes $= \frac{39200}{980} = 40$ grams of force.

Again if a body having a mass of 10 lb. 1 oz. move in a circle of 5 ft. radius with a velocity of 20 ft. per second, then the centripetal force is $f = \frac{10\frac{1}{16} \times 20^2}{5 \times 32.2} = 25$ pounds of force.

129. Illustrations of Centrifugal Force. — Water adhering to the surface of a grindstone leaves the stone as soon as the centrifugal force, increasing with the velocity, is greater than the adhesion of the water to the stone. Grindstones and flywheels occasionally burst when run at too high a speed, the latter when the engine runs away after a heavy load is suddenly thrown off. When the centrip-

etal force is insufficient to deflect the body from the tangent to the circle, the body flies off along the tangent line. A stone is thrown by whirling it in a sling and releasing one of the strings.

A carriage or an automobile rounding a curve at high speed is subject to strong centrifugal forces, which act through the tires. The centripetal force consists solely of the friction between the tires and the ground. If the friction is insufficient, "skidding" takes place.

Centrifugal machines are used in sugar refineries to separate sugar crystals from the syrup, and in dyeworks and laundries to dry yarn and wet clothes by whirling them rapidly in a large cylinder with openings in the side. Honey is extracted from the comb in a similar way. When light and heavy particles are whirled together, the heavier ones tend toward the outside. New milk is an emulsion of fat and a liquid, and the fat globules are lighter than the liquid of the emulsion. Hence, when fresh milk is whirled in a dairy separator, the cream and the milk form distinct layers and collect in separate chambers.

When a spherical vessel containing some mercury and water is rapidly whirled on its axis (Fig. 106), both the mercury and the water rise and form separate bands as far as possible from the axis of rotation, the mercury outside.

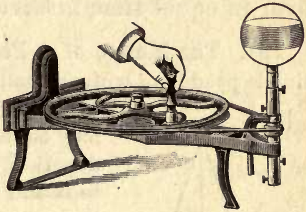


Fig. 106

The figure of the earth is an oblate spheroid, flattened at the poles. This flattening was doubtless caused by the centrifugal force of rotation when the earth was in a plastic state, before it reached its present more rigid condition. Centrifugal force causes the water of the ocean to flow toward the equatorial regions, exposing lands at the north which would be covered with water if the earth were stationary.

VII. THE PENDULUM

130. Simple Pendulum. — Any body suspended so as to swing about a horizontal axis is a *pendulum*. A *simple pendulum* is an ideal one. It may be defined as a material particle without size suspended by a cord without weight. A small lead ball suspended by a long thread

without sensible mass represents very nearly a simple pendulum. When at rest the thread hangs vertically like a plumb line; but if the ball be drawn aside and released, it will *oscillate* about its position of rest. Its excursions on either side become gradually smaller; but if the arc described be small, the period of its swing will remain unchanged. This feature of pendular motion first attracted the attention of Galileo while watching the slow oscillations of a "lamp" or bronze chandelier, suspended by a long rope from the roof of the cathedral in Pisa. Galileo noticed the even time of the oscillations as the path of the swinging chandelier became shorter and shorter. Such a motion, which repeats itself over and over in equal time intervals, is said to be *periodic.*

131. The Motion of a Pendulum. — AN in Fig. 107 is a nearly simple pendulum with the ball at N. When the ball is drawn aside to the position B, its weight, represented by BG, may be resolved into two components, BD in the direction of the thread, and BC at right angles to it and tangent to the arc BNE. The latter is the force which produces motion of the ball toward N.

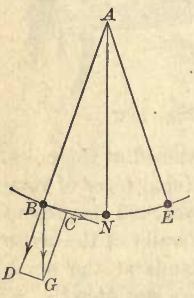


Fig. 107

As the ball moves from B toward N the component BC becomes smaller and smaller and vanishes at N, where the whole weight of the ball is in the direction of the thread. In falling from B to N, the ball moves in the arc of a circle under the influence of a force which is greatest at B and becomes zero at N. The motion is therefore accelerated all the way from B to N, but not uniformly. The velocity increases continuously from B to N, but at a decreasing rate.

The ball passes N with its greatest velocity and continues on toward E. From N to E the component of the weight along the tangent, which is always directed toward N, opposes the motion and brings the pendulum to rest at E. It then retraces its path and continues to oscillate with a *periodic* and *pendular motion.*

132. Definition of Terms. — The *center of suspension* is the point or axis about which the pendulum swings. A *single vibration* is the motion comprised between two successive passages of the pendulum through the lowest point of its path, as the motion from N to B (Fig. 108) and back to N again. A *complete* or *double vibration* is the motion between two successive passages of the pendulum through the same point and going in the same direction. A complete vibration is double that of a single one. The *period of vibration* is the time consumed in making a complete or double vibration. The *amplitude* is the arc BN or the angle BAN.

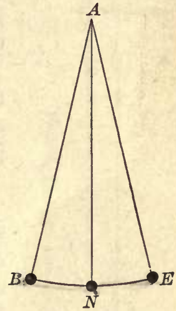


Fig. 108

133. Laws of the Pendulum. — The following are the laws of a simple pendulum:

I. *For small amplitudes, the period of vibration is independent of the amplitude.*

II. *The period of vibration is proportional to the square root of the length.*

III. *The period of vibration is inversely proportional to the square root of the acceleration of gravity.*

One of the earliest and most important discoveries by Galileo was that of the experimental laws of the motion of a pendulum, made when he was about twenty years of age. This was long before their theoretical investigation.

To illustrate law I. It is only necessary to count the vibrations of a pendulum which take place in some convenient time with different amplitudes. Their number will be found to be the same. This result will hold even when the amplitudes are so small that the vibrations can only be observed with a telescope.

To illustrate law II. Mount three pendulums (Fig. 109), making the lengths 1 m., $\frac{1}{4}$ m., and $\frac{1}{9}$ m. respectively. Observe the period of a single vibration for each. They will be 1 sec., $\frac{1}{2}$ sec., and $\frac{1}{3}$ sec. nearly, or in periods proportional to the square root of the lengths.

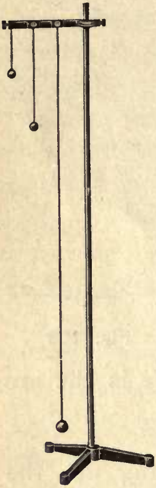


Fig. 109

In accordance with law III a pendulum oscillates more slowly on the top of a high mountain than at sea level, and more slowly at the equator than at the poles.

134. Center of Oscillation — Insert a small staple in one end of a meter stick, and suspend it so as to swing as a pendulum about a horizontal axis through the staple (Fig. 110). With a ball and a thread make a simple pendulum that will vibrate in the same period as the meter stick. Measure the length of this pendulum and lay it off on the meter, beginning at the staple. It will extend two thirds of a meter down. Bore a hole through the meter stick at the point thus found, and suspend it as a pendulum by means of a pin through this hole. Its period of vibration will be the same as before.

Fig. 110

The bar is a compound pendulum, and the new axis of vibration is called the *center of oscillation.* The distance between the center of suspension and the center of oscillation is the length of the equivalent simple pendulum that vibrates in the same period as the compound pendulum. The centers of suspension and of oscillation are interchangeable without change of period.

135. Center of Percussion. — Suspend the meter bar by the staple at the end and strike it with a soft mallet at the center of oscillation. It will be set swinging smoothly and without perceptible jar.

Hold a thin strip of wood a meter long and four or five centimeters wide by the thumb and forefinger near one end. Strike the flat side

with a soft mallet at different points. A point may be found where the blow will not throw the wood strip into shivers, but will only set it swinging like a pendulum.

The center of oscillation is also called the *center of percussion;* if the suspended body be struck at this point at right angles to the axis of suspension, it will be set swinging without jar. A baseball club or a cricket bat has a center of percussion, and it should strike the ball at this point to avoid breaking the bat and "stinging" the hands.

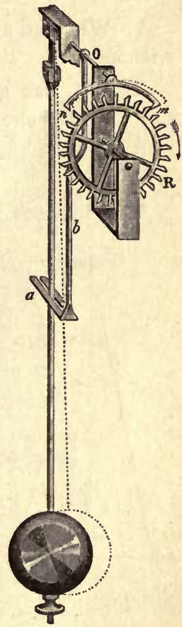


Fig. 111

136. Application of the Pendulum. — Galileo's discovery suggested the use of the pendulum as a timekeeper. In the common clock the oscillations of the pendulum regulate the motion of the hands. The wheels are kept in motion by a weight or a spring, and the regulation is effected by means of the escapement (Fig. 111). The pendulum rod, passing between the prongs of a fork *a*, communicates its motion to an axis carrying the escapement, which terminates in two pallets *n* and *m*. These pallets engage alternately with the teeth of the escapement wheel *R*, one tooth of the wheel escaping from a pallet every double vibration of the pendulum. The escapement wheel is a part of the train of the clock; and as the pendulum controls the escapement, it also controls the motion of the hands.

137. Seconds Pendulum. — A seconds pendulum is one making a single vibration in a second. Its length in New

York is 99.31 cm. This is the length of the equivalent simple pendulum vibrating seconds. The value of gravity g increases from the equator to the poles, and the length of the seconds pendulum increases in the same proportion.

Questions and Problems

1. Why can a boy throw a stone so much farther with a sling than without it?

2. Why can an athlete throw a hammer so much farther than he can "put the shot" of the same mass?

3. Why is the outer rail on a railway curve elevated above the inner one?

4. Why does a bicycle rider lean inward when running round a curve?

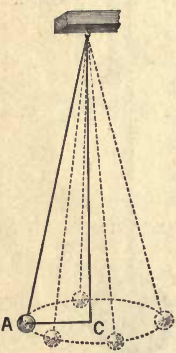


Fig. 112

5. A string attached to a mass of 100 gm. broke when the mass was whirled about the hand at a distance of 1 m., and at the rate of 10 revolutions in 3 seconds. Compute the breaking force in dynes.

6. A mass of 50 gm. is connected to a fixed point by a string 2 m. long, and is whirled round in a circle once in 3 seconds. Find the tension in the string in dynes; also in grams of force.

7. A ball was mounted to swing as a conical pendulum (Fig. 112); its mass was 2 kgm., its distance CA from the center of its circular path was 50 cm., and it made 10 revolutions in 5 seconds. What horizontal force in grams would be necessary to hold the ball out at A if it were not revolving?

8. Two pendulums of the same length have different bobs, one of lead, and the other of aluminum. Will their periods be the same? Why?

CHAPTER VI

MECHANICAL WORK

I. WORK AND ENERGY

138. Work. — A man does work in climbing a hill by lifting himself against the pull of gravity; a horse does work in drawing a wagon up an inclined roadway; a locomotive does work in hauling a train on the level against frictional resistances; gravity does work against the inertia of the mass when it causes the weight of a pile driver (Fig. 113) to descend with increasing velocity; steam does work on the piston of a steam engine and moves it by pressure against a resistance; the electric current does work by means of a motor when it drives an air compressor on an electric car and forces air into a compression tank.

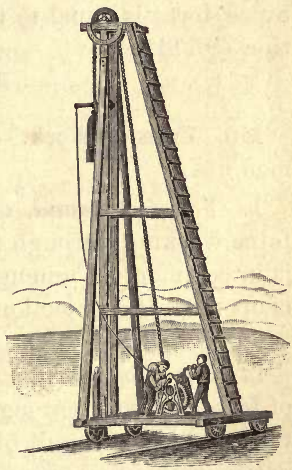


Fig. 113

Whenever an agent exerts force on a body and causes the point of application to move in the direction of the force, the agent is said to do *mechanical work.* Unless the point of application of the force has a component of motion in the direction in which the force acts, no work in a physical sense is done. The columns in a modern steel building do no work, though they sustain great weight; the pillars supporting a pediment over a portico do no work; a person holding a weight suffers

fatigue, but does no work in the sense in which this word is used in physics, where it is employed to describe the *result* and not the *effort* made.

Work is the act of effecting a change in the state of a system against a resistance which opposes the change.

139. Measure of Mechanical Work. — Mechanical work is measured by the product of the force and the displacement of its point of application in the direction in which the force acts, or

$$work = force \times displacement.$$

In symbols $$w = f \times s \quad . \quad . \quad . \quad . \qquad \text{(Equation 15)}$$

Since force is equal to the product of mass and acceleration (§ 114),

$$W = ma \times s. \quad . \quad . \qquad \text{(Equation 16)}$$

140. Units of Work. — Three units of work are in common use:

1. The *foot pound*, or the work done by a pound of force working through a distance of one foot. This unit is in common use among English speaking engineers. It is open to the objection that it is variable, since a pound of force varies with the latitude and with the elevation.

2. The *kilogram meter*, or the work done by a kilogram of force working through a distance of one meter. It is the gravitational unit of work in the metric system, and varies in the same manner as the foot pound.

3. The *erg*,[1] or the work done by a dyne working through a distance of one centimeter. The erg is the absolute unit in the *c. g. s.* system and is invariable.

Since a gram of force is equal to 980 dynes (§ 100), if

[1] The erg is from the Greek word meaning work.

a gram mass be lifted vertically one centimeter, the work done against gravity is 980 ergs. Hence one kilogram meter is equal to $980 \times 1000 \times 100 = 98,000,000$ ergs.

The mass of a "nickel" is 5 gm. The work done in lifting it through a vertical distance of 5 m. is the continued product of 5, 500, and 980, or 2,450,000 ergs. The erg is therefore a very small unit and not suitable for measuring large quantities of work. For such purposes it is more convenient to use a multiple of the erg, called the *joule*.[1] Its value is

$$1\ joule = 10^7\ ergs = 10,000,000\ ergs.$$

Expressed in this larger unit, the work done in lifting the "nickel" is 0.245 joule.

141. Power. — While it takes time to do work, it is plain that time is not an element in the *amount of work done*. To illustrate: Suppose a ton of coal is lifted by a steam engine out of a coal mine through a vertical shaft 300 ft. deep. The work is done by means of a wire rope, which the engine winds on a drum. If now the drum be replaced by another of twice the diameter, and running at the same rate of rotation, the ton of coal will be lifted in half the time; but the work done against gravity remains the same, namely, 600,000 ft. lb.

In an important sense the engine as an agent for doing work is twice as effective in the second instance as in the first. Time is an important element in comparing the capacities of agents to do work. Such a comparison is made by measuring the *power* of an agent.

Power is the time rate of doing work, or

$$power = \frac{work}{time} = \frac{f \times s}{t}. \quad . \qquad \text{(Equation 17)}$$

The unit of power in common use among American and

[1] From the noted English investigator Joule.

English engineers is the *horse power* (H. P.); it is the rate of working equal to 33,000 ft. lb. per minute, or 550 ft. lb. per second. Hence

$$H. P. = \frac{f \times s}{550 \times t}, \quad . \quad . \quad \text{(Equation 18)}$$

in which f is in pounds of force, s in feet, and t in seconds.

In the *c.g.s.* system, the unit of power is the *watt.*[1] It is the rate of working equal to one joule per second. A *kilowatt* (K. W.) is 1000 watts. Hence

$$watts = \frac{f \times s}{t \times 10^7}; \quad K. W. = \frac{f \times s}{t \times 10^{10}}. \quad \text{(Equation 19)}$$

In equation (19) f is in dynes, s in centimeters, and t in seconds.

One horse power equals 746 watts, or 0.746 kilowatt (nearly $\frac{3}{4}$ K.W.). To convert kilowatts into horse powers approximately, add one third; to convert horse powers into kilowatts, subtract one fourth. For example, 60 K.W. are equal to 80 H.P., and 100 H.P. are equal to 75 K.W.

The power capacity of dynamo electric generators is now universally expressed in kilowatts; the steam engines and water turbines used to drive these generators, are commonly rated in the same unit of power; so, too, the capacity of electric motors is more often given in kilowatts than in horse powers. A *kilowatt hour* means power at the rate of a kilowatt expended for one hour. Thus, 20 kilowatt-hours mean 20 K.W. for one hour, or 5 K.W. for four hours, etc.

142. Energy.—Experience teaches that under certain conditions bodies possess the capacity for doing work. Thus, a body of water at a high level, gas under pressure

[1] From the eminent English engineer, James Watt.

in a tank, steam confined in a steam boiler, and the air moving as a wind, are all able to do work by means of appropriate motors. In general, a body or system on which work has been done acquires increased capacity for doing work. It is then said to possess more *energy* than before. *Energy is the capacity for doing work.* It is therefore measured in the same units as work.

143. Potential Energy. — A mass of compressed air in an air gun tends to expand; it possesses energy and may expend it in propelling a bullet. The storage of energy is seen also in the lifted weight of the pile driver, the coiled spring of the clock, the bent bow of the archer, the pent up waters behind a dam, the chemical changes in a charged storage battery, and the mixed charge of gasoline vapor and air in the cylinder of a gas engine.

In all such cases of the storage of energy a *stress* is present. The compressed air pushes outward in the air gun; gravity tugs at the lifted weight; the spring tends to uncoil in the clock; the bent bow strives to unbend; the water presses against the dam; the electric pressure is ready to produce a current; and the explosive gas mixture awaits only a spark to set free its energy. The energy thus stored is called *energy of stress*, or, more commonly, *potential energy.* The energy of an elevated body, of bending, twisting, deformation, of chemical separation, and of the stress in a magnetic field are all examples of potential energy.

144. Kinetic Energy.—The energy which a body has in consequence of its motion is known as *kinetic energy.* The descending hammer forces the nail into the wood; the rushing torrent carries away bridges and overturns buildings; the swift cannon ball, by virtue of its high

speed, demolishes fortifications or pierces the harveyized steel armor of a battleship; the energy stored in the massive rotating flywheel keeps the engine running and does work after the steam is shut off.

Kinetic energy must not be confused with force. A mass of moving matter carries with it kinetic energy, but it exerts no force until it encounters resistance. Energy is then transferred to the opposing body, and force is exerted only during the transfer.

145. Measure of Energy. — Energy is measured in the same terms as those used in measuring work. In general, *potential energy* is the measure of the mechanical work done in storing the energy, or

$$\text{P. E.} = f \times s. \quad . \quad . \quad \text{(Equation 20)}$$

The potential energy of a body of water, for example, of weight w and at an elevation h, is wh gravitational units.

For *kinetic energy*, suppose a force f to act on a mass m for a period of time t; the measure of the effect is the impulse ft (§ 111). If the velocity acquired from rest in the time t is v, the momentum produced is mv. By the second law of motion impulse equals the momentum imparted. Therefore

$$ft = mv. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (a)$$

A constant force applied to a body gives rise to uniformly accelerated motion; and if the body starts from rest, the mean velocity is $\frac{1}{2}v$. It is also the space traversed divided by the time, or $\frac{s}{t}$. Hence, equating the two expressions for the mean velocity,

$$\frac{s}{t} = \frac{1}{2}v. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (b)$$

Multiply (*a*) and (*b*) together, member by member, and the result is

$$fs = \frac{1}{2} mv^2. \quad . \quad . \quad \text{(Equation 21)}$$

But fs measures the work done by the force f on the mass m to give to it the velocity v, while working through the distance s; and since the kinetic energy acquired by a body is measured by the work done on it to give it motion, it follows that the energy of the mass m moving with the velocity v is $\frac{1}{2} mv^2$, or

$$\text{K. E.} = \frac{1}{2} mv^2. \quad . \quad . \quad \text{(Equation 22)}$$

If m is expressed in grams and v in centimeters per second, the result is in ergs. To reduce to gram centimeters, divide by the value of g in centimeters per second per second, or 980. If m is in pounds and v in feet per second, to obtain the energy in foot pounds, divide by the value of g in feet per second per second, or 32.2.

146. Transformations of Energy. — When a bullet is shot vertically upward, it gradually loses its motion and its kinetic energy, but gains energy of position or potential energy. When it reaches the highest point of its flight, its energy is all potential. It then descends, and gains energy of motion at the expense of energy of position. The one form of energy is, therefore, convertible into the other.

The pendulum illustrates the same principle. While the bob is moving from the lowest point of its path toward either extremity, its kinetic energy is converted into potential energy; the reverse transformation sets in when the pendulum reverses its motion. All physical processes involve energy changes, and such changes are in ceaseless progress.

147. Conservation of Energy. — Whenever a body gains energy as the result of work done on it, it is always at the expense of energy in some other body or system. The agent, or body, which does work always loses energy; the body which has work done on it gains energy equal to the work done. On the whole there is neither gain nor loss of energy, but only its transfer from one body to another. Innumerable facts and observations show that it is as impossible to create energy as it is to create matter. So the law of *conservation of energy* means that *no energy is created and none destroyed by the action of forces we know anything about.*

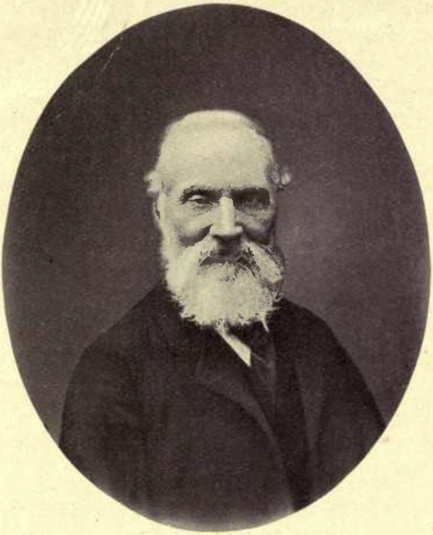
148. Dissipation of Energy. — Potential energy is the more highly available or useful form of energy. It always tends to go over into the kinetic type, but in such a way that only a portion of the kinetic energy is available to effect useful changes in nature or in the mechanic arts. The remainder is dissipated as heat. *This running down of energy by passing into an unavailable form is known as the dissipation of energy.* It was first recognized and distinctly stated by Lord Kelvin in 1859.

The capacity which a body possesses for doing work does not depend on the total quantity of energy which it may possess, but only on that portion which is *available*, or is capable of being transferred to other bodies. In the problems of physics our chief concern is with the variations of energy in a body and not with its total value.

Questions and Problems

1. Why will a cord supporting a weight generally break if the weight be lifted and then let fall?

2. A stick resting across two blocks may be strong enough to bear your weight, but will break if you jump on it. Explain.



Lord Kelvin (Sir William Thomson), 1824–1907, was born at Belfast. He graduated at Cambridge in 1845 and in the same year received the appointment of professor of natural philosophy in the University of Glasgow, a position which he held for fifty-three years. He was one of the greatest mathematical physicists of his day. His invention of the astatic mirror-galvanometer and the siphon-recorder has made successful marine cables a reality. His laboratory for the use of students was the first of the kind to be established. His most noteworthy investigations were in heat, energy, and electricity, yet there is scarcely any portion of physical science that has not been greatly enriched by his genius.

3. Lake Tahoe, in the Sierra Nevada, is at an elevation of 6225 ft. above the sea. Account for the energy stored there in the water.

4. In what form is the energy for driving a steamship taken on board? Is the energy driving a sailing vessel potential or kinetic? In what form is it supplied to an automobile; to an aëroplane; to a man?

5. How much work is done in lifting a stone weighing 100 kgm. to the top of a building 20 m. high? What is its potential energy at the top?

6. A rectangular marble slab 6 ft. 3 in. long, 3 in. thick, and weighing 500 lb. lies on a level floor. How much work must be done to set it vertically on end?

7. A baseball whose mass is 150 gm. is moving with a velocity of 5000 cm. per second. What is its kinetic energy in ergs? How much work would be done in stopping it?

8. What is the kinetic energy of a 5-gm. bullet when fired with a velocity of 300 m. per second?

9. A force of 200 dynes moves a mass of 100 gm. through a distance of 50 cm. in 10 sec. How much work is done?

10. A pull of 50 lb. moves a 100-lb. truck through a distance of 200 ft. How much work in foot pounds is done?

11. A load weighing 2 tons was drawn up a hill half a mile long by a traction engine. The hill was 100 ft. high. How much work was done against gravity?

12. How much work can a 40 H. P. engine do in an hour? How much coal can it lift out of a mine 400 ft. deep in 10 hrs.?

13. A thousand-barrel tank at a mean elevation of 50 ft. is filled with water. How much work was done in filling it, assuming a barrel of water to weigh 260 lb.? How long would it take a motor, working at a 2 H. P. rate, to pump it full?

14. An electric motor rated at 100 K. W. is used to operate a pump. The water has to be lifted to a mean height of 100 m. How many liters can the motor pump in an hour?

15. What is the power of an agent that lifts 1000 kgm. 10 m. high in 10 min.? Express the result in K. W.

16. Express in joules the work done by 100 kgm. of force in moving a mass of 100 kgm. through a distance of 100 m. in the direction of the force.

17. The average pressure of steam on the piston of a steam engine is 120 lb. of force per square inch. The area of the piston is 50 sq. in. The piston travels 30 in. during one complete revolution of the flywheel, and the flywheel makes 220 revolutions per minute. What is the H. P. of the engine?

18. A railway train weighs 250 tons, and the resistance to its motion on a level track is 15 lb. of force per ton. What H. P. must the locomotive develop to maintain a speed of 40 mi. an hour on the level?

19. How many H. P. are transmitted by a rope passing over a wheel 33 ft. in circumference and making one revolution per second, the tension in the rope being 100 lb. of force?

20. A ball whose mass is 100 gm. is struck with a club and is given a velocity of 40 m. per second. How much energy is imparted by the blow?

21. A train weighing 150 tons and running at the rate of 30 mi. an hour is brought to rest by the air brakes within a distance of 500 ft. Find the force of the brakes.

22. A constant resistance of 1000 dynes is applied to a body of 200 gm. mass, moving with a velocity of 6 m. per minute and brings it to rest. How far did the body move after the resistance was applied?

II. MACHINES

149. What a Machine is. — A *machine* is a device designed to change the direction or the magnitude of a force required to do useful work, or one to transform and transfer energy.

Illustrations. — By the use of a single pulley, the direction of the applied force may be changed, so as to lift a weight, for example, while the force acts in any desired direction. A water wheel transforms the potential and kinetic energy of falling water into mechanical energy represented by the energy of the rotating wheel. A dynamo electric machine transforms mechanical energy into the energy of an electric current, and an electric motor at a distance transforms the electric energy back again into mechanical work.

150. General Law of Machines. — Every machine must conform to the principle of the conservation of energy; that is, *the work done by the applied force equals the work done in overcoming the resistance*, except that some of the applied energy may be dissipated as heat or may not appear in mechanical form. A machine can never produce an increase of energy so as to give out more than it receives.

Denote the applied force, or *effort*, by E and the *resistance* by R, and let D and d denote the distances respectively through which they work. Then from the law of conservation of energy, the effort multiplied by the distance through which it acts is equal to the resistance multiplied by its displacement, or

$$ED = Rd. \quad \text{(Equation 23)}$$

151. Friction. — *Friction is the resistance which opposes an effort to slide or roll one body over another.* It is called into action whenever a force is applied to make one surface move over another. Friction arises from irregularities in the surfaces in contact and from the force of adhesion. It is diminished by polishing and by the use of lubricants.

Experiments show that friction (*a*) is proportional to the pressure between the surfaces in contact, (*b*) is independent of the area of the surfaces in contact within certain limits, and (*c*) has its greatest value just before motion takes place. The friction of a solid rolling on a smooth surface is less than when it slides. Advantage is taken of this fact to reduce the friction of bearings. A ball bearing (Fig. 114) substitutes the rolling friction between balls and rings for the sliding friction between a shaft and its journal.

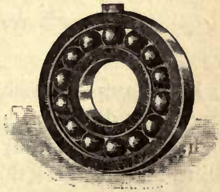


Fig. 114

152. Advantages and Disadvantages of Friction. — Friction has innumerable uses in preventing motion between surfaces in contact. Screws and nails hold entirely by friction; we are able to walk because of friction between the shoe and the pavement; shoes with nails in the heels are dangerous on cast-iron plates because the friction between smooth iron surfaces is small. Friction is useful in the brake to stop a motor car or railway train, in holding the driving wheels of a locomotive to the rails, and in enabling a gasoline engine to drive an automobile by friction between the tires and the street.

On the other hand friction is also a resistance opposing useful motion, and whenever motion takes place, work must be done against this frictional resistance. The energy thus consumed is converted into heat and is no longer available for useful work.

153. Efficiency of Machines. — On account of the impossibility of avoiding friction, every machine wastes energy. The work done is, therefore, partly *useful* and partly *wasteful*. *The efficiency of a machine is the ratio of the useful work done by it to the total work done by the acting force*, or

$$\textit{efficiency} = \frac{\textit{useful work done}}{\textit{total energy applied}}.$$

For example, an effort of 100 pounds of force applied to a machine produces a displacement of 40 ft. and raises a weight of 180 lb. 20 ft. high. Then $100 \times 40 = 4000$ ft. lb. of energy are put into the machine, and the work done is $180 \times 20 = 3600$ ft. lb.

Hence $\qquad \textit{efficiency} = \frac{3600}{4000} = 0.9 = 90$ per cent.

Ten per cent of the energy is wasted and ninety per cent recovered.

Since every machine wastes energy, a machine which will do either useful or useless work continuously without a supply of energy from without, a so-called "perpetual motion machine," is thus clearly impossible.

Let e denote the efficiency of a machine, then from the relations just explained, equation (23) becomes

$$eED = RD. \quad . \quad . \quad . \quad \text{(Equation 24)}$$

This relation is the strictly correct one to apply to all machines; but in most problems dealing with simple machines, friction is neglected.

154. Simple Machines. — All machines can be reduced to six *mechanical powers* or *simple machines:* the *lever*, the *pulley*, the *inclined plane*, the *wheel and axle*, the *wedge*, and the *screw.* Since the wheel and axle is only a modified lever, and the wedge and the screw are modifications of the inclined plane, the mechanical powers may be reduced to three. In all cases, neglecting friction, the law expressed by equation (23) holds good.

155. Mechanical Advantage. — A man working a pump handle and pumping water is an agent *applying energy;* the pump and the water compose a system *receiving energy.* In a simple machine the force exerted by the agent applying energy, and the opposing force of the system receiving energy, may be denoted by the two terms, *effort*, E, and *resistance*, R. The problem in simple machines consists in finding the ratio of the resistance to the effort.

The ratio of the *resisting force R to the applied force E is called the mechanical advantage of the machine.* This ratio may always be expressed in terms of certain parts of simple machines.

156. Moment of a Force. — In the application of the lever, the pulley, or the wheel and axle there is motion about an axis. The application of a single force to a body with a fixed axis produces rotation only. Examples are a door swinging on its hinges and the flywheel of an engine.

The effect of a force in producing rotation depends, not only on the value of the force, but on the distance of its line of application from the axis of rotation. A smaller force is required to close a door when it is applied at right angles to the door at the knob than when it is applied near the hinge. Also, an increase in the speed of rotation of a flywheel may be secured either by increasing the applied force or by lengthening the crank. Both these elements of effectiveness are included in what is known as the *moment of a force.*

The moment of a force is the product of the force and the perpendicular distance between its line of action and the axis of rotation. Let M be a body which may rotate about an axis through O (Fig. 115). The moment of the force F applied at B in the direction CB is $F \times OB$; applied in the direction AB, its moment is $F \times OA$. The point O is called the *center of moments.*

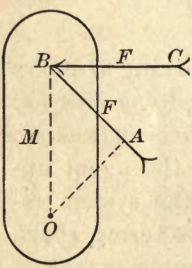


Fig. 115

A moment is considered positive if it produces rotation in a clockwise direction, and negative if in the other. *If the sum of the positive moments equals that of the negative moments, there is equilibrium.*

157. The Lever. — The lever is more frequently used than any other simple machine. In its simplest form

the lever is a rigid bar turning about a fixed axis called the fulcrum. It is convenient to divide levers into three classes, distinguished by the relative position of the fulcrum with respect to the two forces. In the *first class* the fulcrum is between the effort E and the resistance R (Fig. 116); in the *second class* the resistance is between the effort and the fulcrum; in the *third class* the effort is between the resistance and the fulcrum.

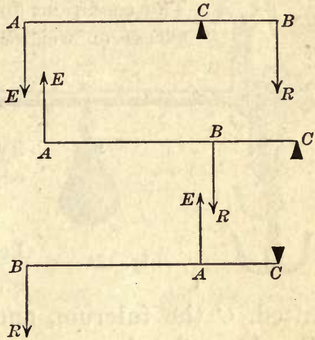


Fig. 116

158. Examples of Levers. — A *crowbar* used as a pry (Fig. 117) is a lever of the first class, but when used to lift a weight with one end on the ground (Fig. 118), it is a lever of the second class.

Fig. 117

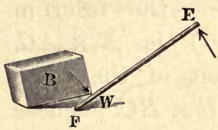


Fig. 118

Scissors are double levers of the first class. So also are the *tongs* of a blacksmith, and those used in chemical laboratories for lifting crucibles (Fig. 119). The *forearm* when it supports a weight

Fig. 119

Fig. 120

in the extended hand, and the *door* when it is closed by pushing it near the hinge, are examples of levers of the third class. *Nutcrackers* (Fig. 120) and *lemon squeezers* are double levers of the second class.

The *steelyard* (Fig. 121) is a lever of the first class with unequal arms. The *common balance* (Fig. 122) is a lever of the first class with equal arms. The two weights are thus also equal. The conditions for a sensitive balance, to show a small excess of weight in one pan over that in the other, are small friction at the fulcrum, a light beam, and the center of gravity only slightly lower than the "knife-edge" forming the fulcrum.

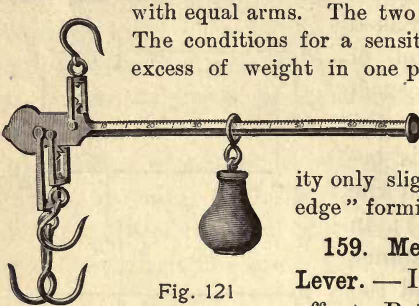


Fig. 121

159. Mechanical Advantage of the Lever. — In Fig. 123 E is the effort, R the resistance or weight lifted, C the fulcrum, and AC and BC the lever arms. Consider the lever to be weightless and to rotate about C without friction; then the moment of the force E about the fulcrum (§ 156) is $E \times AC$, and that of the force R is $R \times BC$. These two forces tend to produce rotation in opposite directions; for equilibrium their moments are therefore equal, that is, $E \times AC = R \times BC$; from which

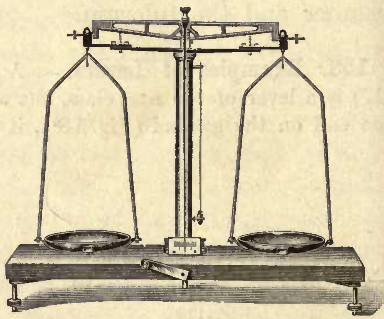


Fig. 122

$$\frac{R}{E} = \frac{AC}{BC}.$$

(Equation 25)

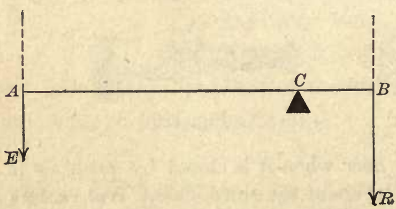


Fig. 123

Hence, *the mechanical advantage of the lever equals the inverse ratio of its arms.*

If the weight of the lever has to be taken into account, it is to be treated as a force acting at the center of gravity of the lever, and its moment must be added to that of the force turning the lever in the same direction as its own weight.

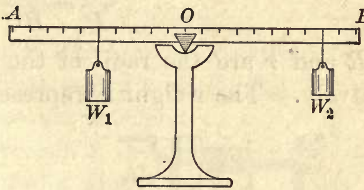


Fig. 124

EXAMPLE. — The weights W_1 and W_2 are placed at distances 5 and 8 units respectively from O (Fig. 124). If W_1 is 20 lb., what must W_2 be for equilibrium? By the principle of moments about O,

$$20 \times 5 = W_2 \times 8;$$

whence $$W_2 = 12.5 \text{ lb.}$$

If the lever is uniform, it is balanced about the fulcrum O and its moment is zero. Suppose the weight of the bar to be 1 lb. and its center of gravity 4 units to the left of O. The equation for equilibrium would then be

$$20 \times 5 + 1 \times 4 = W_2 \times 8.$$

Whence $$W_2 = 13 \text{ lb.}$$

160. The Wheel and Axle consists of a cylinder and a wheel of larger diameter usually turning together on the same axis. In Fig. 125 the axle passes through C, the radius of the cylinder is BC, and that of the wheel is AC. The weights P and W are suspended by ropes wrapped around the circumference of the two wheels; their moments about the axis O are $P \times AC$ and $W \times BC$ respectively. For

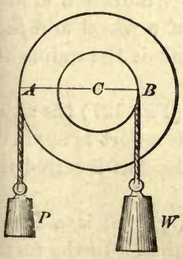


Fig. 125

equilibrium these moments are equal, that is, $P \times AC = W \times BC$. Hence,

$$\frac{W}{P} = \frac{AC}{BC} = \frac{R}{r}. \quad \cdot \quad \cdot \quad \cdot \quad \text{(Equation 26)}$$

$\boldsymbol{R}$ and $\boldsymbol{r}$ are the radii of the wheel and the axle respectively. The weight P represents the effort applied at the

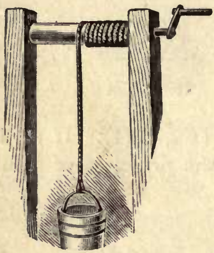


Fig. 126

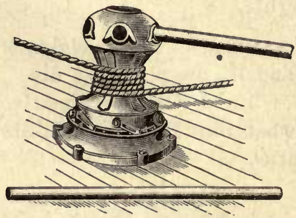


Fig. 127

circumference of the wheel, and the weight W the resistance at the circumference of the axle. Therefore, *the mechanical advantage of the wheel and axle is the ratio of the radius of the wheel to that of the axle.*

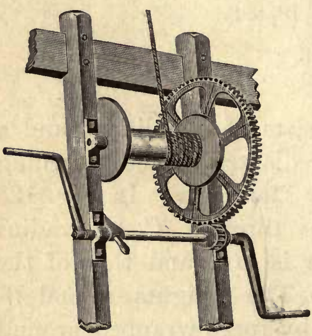


Fig. 128

161. Applications. — The old well windlass for drawing water from deep wells (Fig. 126) by means of a rope and bucket is an application of the principle of the wheel and axle. In the windlass a crank takes the place of a wheel and the length of the crank is the radius of the wheel.

In the *capstan* (Fig. 127) the axle is vertical, and the effort is applied by means of handspikes inserted in holes in the top.

The *derrick* (Fig. 128) is a form of wheel and axle much used for raising heavy weights. In the form shown it is essentially a double wheel and axle. The axle of the

first system works upon the wheel of the second by means of the spur gear. *The mechanical advantage of such a compound machine is the ratio of the product of the radii of the wheels to the product of the radii of the axles.*

162. The Pulley *consists of a wheel, called a sheave, free to turn about an axle in a frame, called a block* (Fig. 129). The effort and the resistance are attached to a rope which moves in a groove cut in the circumference of the wheel. A simple *fixed pulley* is one whose axis does not change its position; it is used to change the direction of the applied force (Fig. 130). If friction and the rigidity of the rope are neglected, the tension in the rope is everywhere the same; the effort and the resistance are then equal to each other and the mechanical advantage is unity.

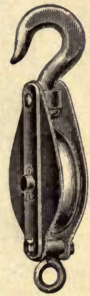


Fig. 129

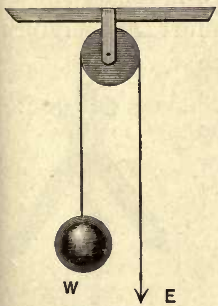


Fig. 130

In the movable pulley (Fig. 131) it is evident that the weight W is supported by two parts of the cord, one half of it by means of the hook fixed in the beam above and the other half by the effort E applied at the free end of the cord. If the weight is lifted, it rises only half as fast as the cord travels.

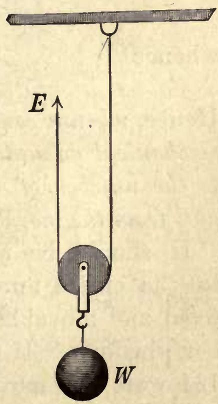


Fig. 131

163. Systems of Fixed and Movable Pulleys. — Fixed and movable pulleys are combined in a great variety of ways. The most common is the one

employing a continuous cord. Figure 132 represents a combination of one fixed and one movable pulley. Figure 133 illustrates the common "block and tackle," where each block has more than one sheave.

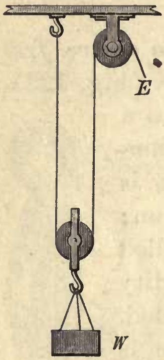


Fig. 132

164. Mechanical Advantage of the Pulley. — In Fig. 134 the cord passes in succession around each pulley. It is evident that if the movable pulley and the resistance R are moved toward the fixed pulley a distance a, each cord passing between the two blocks must be shortened by a units. The effort E therefore travels through a distance of na units, n being the number of parts to the cord between the two pulleys. Then by the general law of machines (§ 150),

$$E \times na = R \times a;$$

whence $$\frac{R}{E} = n. \quad \text{(Equation 27)}$$

Hence, *when a continuous cord is used, the mechanical advantage of the pulley is equal to the number of times the cord passes to and from the movable block.*

It should be noticed that n is equal to the entire number of sheaves in the fixed and movable blocks, or to that number plus one. If the upper block in Fig. 134 were the movable one, that is, if the system were inverted so that the effort E

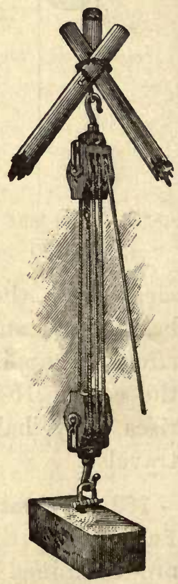


Fig. 133

is upward, n would be equal to one more than the number of sheaves.

165. The Inclined Plane. — If a body rests on an inclined plane without friction, the weight of the body acts vertically downward, while the reaction of the plane is perpendicular to its surface; hence a third force must be applied to maintain the body in equilibrium on the incline. This force may be applied (1) parallel to the *face* of the plane; or (2) parallel to the *base* of the plane.

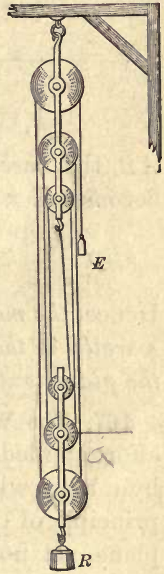


Fig. 134

166. Mechanical Advantage of the Inclined Plane. — *Case I: When the effort is applied parallel to the face of the plane* (Fig. 135). The most convenient way to find the relation between the force E and the weight W of the body D is to apply the principle of work (§ 139). Suppose D to be moved by the force E from A to C. Then the work done by E is $E \times AC$. Since the body D is lifted through a vertical distance BC, the work done on it against gravity is $W \times BC$. Therefore, $E \times AC = W \times BC$, and

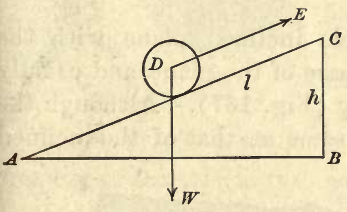


Fig. 135

$$\frac{W}{E} = \frac{AC}{BC} = \frac{l}{h}, \quad \cdot \quad \cdot \quad \text{(Equation 28)}$$

or, *the mechanical advantage, when the effort is applied parallel to the face of the plane, is the ratio of the length of the plane to its height.*

Case II: When the effort is applied parallel to the base of the plane (Fig. 136). In expressing the work done by the force E in moving the body up the plane from A to C, we must take the displacement measured in the direction in which the force acts. This displacement in this case is not AC, but AB, the base of the plane. Then the general equation becomes $E \times AB = W \times BC$, and

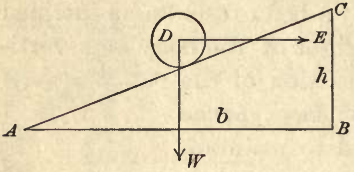


Fig. 136

$$\frac{W}{E} = \frac{AB}{BC} = \frac{b}{h}. \quad . \quad . \quad \text{(Equation 29)}$$

Hence, *the mechanical advantage, when the effort is applied parallel to the base of the plane, is the ratio of the base of the plane to its height.*

167. The Wedge is a double inclined plane with the effort applied parallel to the base of the plane, and usually by a blow with a heavy body (Fig. 137). Although the principle of the wedge is the same as that of the inclined plane, yet no exact statement of its mechanical advantage is possible, because the resistance has no definite relation to the faces of the planes, and the friction cannot be neglected. Many cutting instruments, such as the ax and the chisel, act on the principle of the wedge; also nails, pins, and needles.

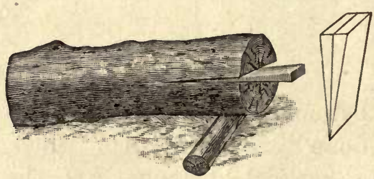


Fig. 137

168. The Screw is a cylinder, on the outer surface of which is a uniform spiral projection, called the *thread.*

The faces of this thread are inclined planes. If a long triangular strip of paper be wrapped around a pencil (Fig. 138), with the base of the triangle perpendicular to the axis of the cylindrical pencil, the hypotenuse of the triangle will trace a spiral like the thread of a screw.

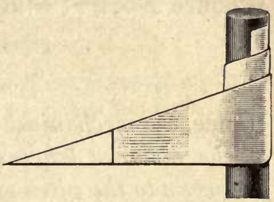


Fig. 138

The screw (Fig. 139) works in a block called a *nut*, on the inner surface of which is a groove, the exact counterpart of the thread. The effort is applied at the end of a lever or wrench, fitted either to the screw or to the nut. When either makes a complete turn, the screw or the nut moves through a distance equal to that between two adjacent threads, measured parallel to the axis of the screw cylinder. This distance, s in Fig. 140, is called the *pitch* of the screw. It is usually expressed as the number of threads to the inch or to the centimeter.

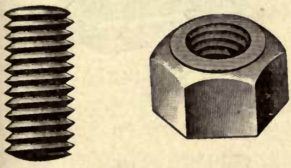


Fig. 139

169. Mechanical Advantage of the Screw. — Since the screw is usually combined with the lever, the simplest method of finding the mechanical advantage is to apply the principle of work, as expressed in the general law of machines (§ 150). If the pitch be denoted by s and the resistance overcome by R, then, ignoring friction, the work done against R in one revolution

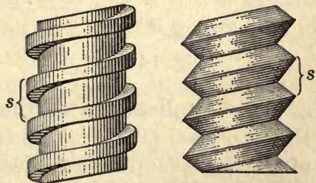


Fig. 140

of the screw is $R \times s$. If the length of the lever is l, the work done by the effort E in one revolution is $E \times 2\pi l$. Whence $E \times 2\pi l = R \times s$, or

$$\frac{R}{E} = \frac{2\pi l}{s}. \quad . \quad . \quad . \text{(Equation 30)}$$

Hence, *the mechanical advantage of the screw equals the ratio of the distance traversed by the effort in one revolution of the screw to the pitch of the screw.*

Fig. 141

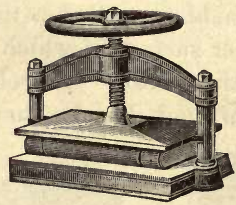


Fig. 142

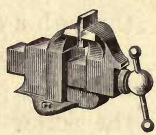


Fig. 143

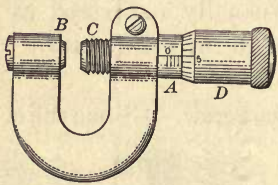


Fig. 144

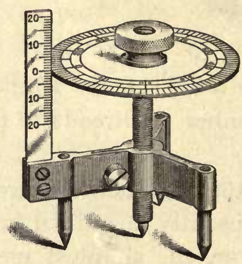


Fig. 145

170. Applications of the Screw. — The *jackscrew* (Fig. 141), the *letter press* (Fig. 142), the *vise* (Fig. 143), and the *screw propeller* of a ship are familiar examples of the use of the screw.

An important application of the screw, though not as a machine, is that for measuring small dimensions. The wire *micrometer* (Fig. 144) and the *spherometer* (Fig. 145) are instruments for this purpose. In both, an accurate screw has a head divided into a number of equal

parts, 100 for example, so as to register any portion of a revolution. If the pitch of the screw is 1 mm., then turning the head through one of its divisions causes the screw to move parallel to its axis 0.01 mm.

Questions and Problems

1. What are the relative positions of the effort, the resistance, and the fulcrum in the following instruments : a pump handle, a pitch-fork, a can opener, a pair of sugar tongs, an oar, and a claw hammer?

2. In which direction does friction on the rails act on the wheels of a locomotive? On those of a freight car? Does it act in the same direction on the front and the rear wheels of an automobile?

3. Calculate the efficiency of a machine when an effort of 50 lb. of force acting through 30 ft. lifts a weight of 200 lb. a distance of 6 ft. (§ 153).

4. If in a system of pulleys a tension of 45 kgm. of force is applied to the rope and the rope is drawn 60 ft., while a weight of 250 kgm. is lifted 10 ft., what is the efficiency of the system (§ 153)?

5. If in a lever of the first class a weight of 100 kgm. is placed at a distance of 10 cm. from the fulcrum, what weight would have to be placed 50 cm. from the fulcrum to balance it?

6. A weight of 50 lb. is placed 15 in. from the fulcrum in a lever of the second class. The effort is 5 lb. of force. Find the length of the lever.

7. A uniform bar, weighing 2 lb. to the foot, is 20 ft. long. It is used as a lever of the first class to lift a weight of 475 lb. The fulcrum is 2 ft. from one end. Find the effort necessary to balance the weight (§ 156).

8. A uniform bar 2 m. long and weighing 4 kgm. has weights of 7 kgm. and 15 kgm. suspended at its two ends. Where must the fulcrum be placed for equilibrium?

SUGGESTION. Let x be the distance of the fulcrum from the weight of 7 kgm.; then the distance of the center of gravity of the bar from the fulcrum is $x-1$, and that of the weight of 15 kgm. is $2-x$.

9. In a wheel and axle the diameter of the axle is 40 cm., and to it is attached by a rope a weight of 500 kgm. The axle is turned by a lever 1 m. long. Find the effort necessary for equilibrium.

10. The diameter of the cylinder of a ship's capstan is 12 in. What force would have to be applied to a handspike at an effective

distance of 6 ft. in order to turn the capstan and lift an anchor weighing 2400 lb.?

11. In the block and tackle shown in Fig. 133 there are three sheaves in each block. What weight will a force of 200 lb. lift, neglecting friction?

12. How many sheaves would be required, in a system like that of Fig. 133, in order that an effort of 100 lb. should just balance a weight of 800 lb.?

13. A cart weighing 210 kgm. is to be pushed up an inclined plane by a force of 15 kgm. If the height of the plane is 5 m., what must be its length, neglecting friction?

14. The efficiency of an inclined plane is 80 per cent. If the length of the plane is 25 ft. and its height 5 ft., what effort acting parallel to the face of the plane will be required to move a body weighing 400 lb. up the plane (§ 153)?

15. The screw of a letter press has five threads to the inch, the diameter of the wheel is 12 in., and the effort applied to it is 40 lb. of force. Neglecting friction, what is the pressure of the plate?

16. A weight of 1000 lb. is raised by a jackscrew. What force must be applied, in addition to the force required to overcome friction, if the lever is 2 ft. long and the screw has five threads to the inch?

17. The radii of a wheel and axle are 5 ft. and 5 in. respectively. It was found that a force of 100 lb. can lift a weight of 960 lb. What weight would 100 lb. of force lift if there were no friction? What is the efficiency of the machine?

18. If the front sprocket wheel of a bicycle contains 24 sprockets and the rear one 8, how far will one complete turn of the pedals drive a 28 in. wheel?

19. The diameter of the large driving wheel of a sewing machine is 12.5 in. and that of the small driven wheel is 3 in. If the slip of the belt is 4 per cent., how many stitches does the machine make for every up-and-down movement of the treadle?

20. An automobile engine makes 900 revolutions per minute when driving the shaft direct. The spur wheels in the differential give a ratio between the revolutions of the shaft and that of the axle of one to four. With 36 in. wheels the slipping on the ground is enough to reduce the distance traveled every revolution to 9 ft. What is the speed of the automobile in miles per hour?

CHAPTER VII

SOUND

I. WAVE MOTION

171. Vibrations. — A *vibrating* or *oscillating* body is one which repeats its limited motion at regular short intervals of time. A *complete* or *double vibration* is the motion between two successive passages of the moving body through any point of its path *in the same direction.*

If we suspend a ball by a long thread and set it swinging like a common pendulum, it will return at regular intervals to the starting point. If we set the ball moving in a circle, the string will describe a conical surface and the ball will again return *periodically* to the point of departure.

172. Kinds of Vibration. — Clamp one end of a thin steel strip in a vise (Fig. 146); draw the free end aside and release it. It will move repeatedly from D' to D'' and back again. The shorter or thicker the strip, the quicker its vibrations; when it becomes like the prong of a tuning fork, it emits a musical sound.

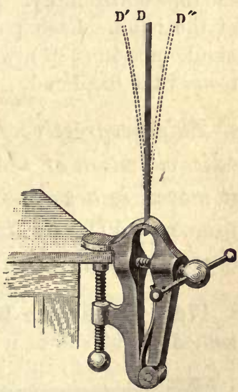


Fig. 146

Vibrations like these are *transverse. A body vibrates transversely when the direction of the motion is at right angles to its length.* The strings of a violin, the reeds of a cabinet organ, and the wires of a piano are familiar examples.

Fasten the ends of a long spiral spring securely to fixed supports with the spring slightly stretched. Crowd together a few turns of the spiral at one end and release them. A vibratory movement will travel from one end of the spiral to the other, and each turn of wire will swing backward and forward in the direction of the length of the spiral (Fig. 147).

Fig. 147

The vibrations of the spiral are longitudinal. *A body vibrates longitudinally when its parts move backward and forward in the direction of its length.* The vibrations set up in a long glass tube by stroking it lengthwise with a damp cloth are longitudinal; so are those of the air in a trumpet and the air in an organ pipe.

173. Wave Motion. — Tie one end of a soft cotton rope, such as a clothesline, to a fixed support; grasp the other end and stretch the rope horizontally. Start a disturbance by an up-and-down motion of the hand. Each point of the rope will vibrate with simple harmonic motion (§ 97), while the disturbance will travel along the rope toward the fixed end.

This progressive form or change in shape, due to the periodic vibration of the particles of the medium through which it moves, is a wave. The particles are not all in the same phase (§ 175) or stage of vibration, but they pass through corresponding positions in succession.

174. Transverse Waves. — A small camel's-hair brush is attached to the end of a long slender strip of clear wood, mounted as

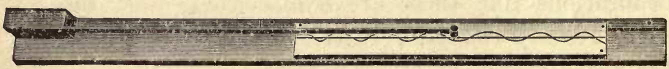


Fig. 148

shown in Fig. 148. The brush should just touch the paper under it. Ink the brush and draw the movable board with the attached paper

under the brush while at rest. The brush will mark the straight middle line running through the curve shown in the figure. Replace the board in the starting position; then pull the strip aside and release it. Again draw the board under the brush with uniform motion. This time the brush traces the curved line. It is an *harmonic curve* or *graphic wave form.*

Suppose a series of particles, originally equidistant, to vibrate transversely with simple harmonic motion. Let Fig. 149 represent the position of the particles at some

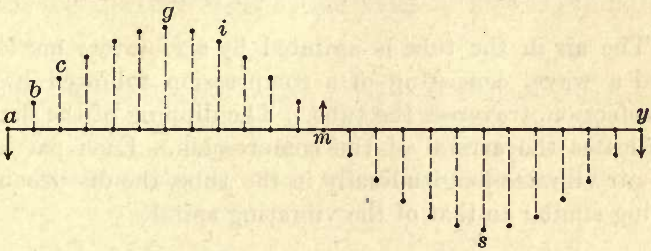


Fig. 149

particular instant. The particle at *g* has reached its maximum displacement in one direction and the one at *s* the maximum in the other. At *m* the particle is moving with its greatest velocity in one direction, and the particle at *y* with its greatest velocity in the other direction. If the wave is traveling toward the right, a moment later the transverse displacement of *g* will be less and that of *i* a maximum, the crest of the wave having moved forward from *g* to *i*. The successive particles all differ in phase by the same amount.

A transverse wave is one in which the vibration of the particles is at right angles to the direction in which the wave is traveling.

175. Longitudinal Waves. — Place a lighted candle at the conical end of the long tin tube of Fig. 150. Over the other end

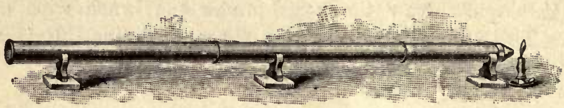


Fig. 150

stretch a piece of parchment paper. Tap the paper lightly with a cork mallet; the transmitted impulse will cause the flame to duck, and it may easily be blown out by a sharper blow.

The air in the tube is agitated by a vibratory motion, and a wave, consisting of a compression followed by a rarefaction, traverses the tube. The dipping of the flame indicates the arrival of the compression. Each particle of air vibrates longitudinally in the tube, the disturbance being similar to that of the vibrating spiral.

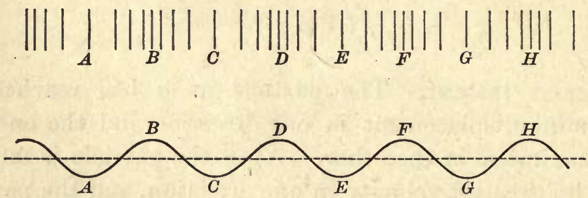


Fig. 151

Figure 151 illustrates the distribution of the air particles when disturbed by such a longitudinal wave of compressions and rarefactions. *B*, *D*, *F*, etc., are regions of compressions; *A*, *C*, *E*, etc., those of rarefaction. The distances of the different points of the curve from the straight line denote the relative velocities of the air particles. *A* and *C*, or *B* and *D*, are in the same *phase*, that is, in corresponding positions in their paths.

A longitudinal wave is one in which the oscillations are backward and forward in the same direction as the wave is traveling.

176. Wave Length. — The *length of a wave* is the distance from any particle to the next one in the *same phase*, as from *a* to *y* (Fig. 149), or from *A* to *C* or *B* to *D* (Fig. 151). Since the wave form travels from *a* to *y*, or from *A* to *C*, during the time of one complete vibration of a particle, it follows that the wave length is the distance traversed by the wave during one vibration period.

177. Water Waves. — One of the most familiar examples of transverse waves are those on the surface of water. For deep water the particles describe circles, all in the same vertical plane containing the direction in which the wave is traveling, as illustrated in Fig. 152.

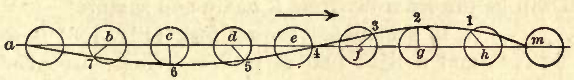


Fig. 152

The circles in the diagram are divided into eight equal arcs, and the water particles are supposed to describe these circles in the direction of watch hands and all at the same rate; but in any two consecutive circles their phase of motion differs by one eighth of a period. When *a* has completed one revolution, *b* is one eighth of a revolution behind it, *c* two eighths or one quarter, etc. A smooth curve drawn through the positions of the particles in the several circles at the same instant is the outline or contour of a wave.

When a particle is at the crest of a wave, it is moving in the same direction as the wave; when it is in the trough, its motion is opposite to that of the wave.

The crests and troughs are not of the same size, and the larger the circles (or amplitude), the smaller are the crests in comparison with the troughs. Hence the crests of high waves tend to become sharp or looped, and they break into foam or white caps.

II. SOUND AND ITS TRANSMISSION

178. Sound *may be defined as that form of vibratory motion in an elastic medium which affects the auditory nerves, and produces the sensation of hearing.* All the external phenomena of sound may be present without the hearing ear. Sound should therefore be distinguished from hearing.

179. Source of Sound. — If we suspend a small elastic ball by a thread so that it just touches the edge of an inverted bell jar, and strike the edge of the jar with a felted or cork mallet, the ball will be repeatedly thrown away from the jar as long as the sound is heard. This shows that the jar is vibrating energetically.

Stretch a piano wire over the table and a little above it. Draw a violin bow across the wire, and then touch it with the suspended ball of the previous paragraph. So long as the wire emits sound the ball will be thrown away from it again and again.

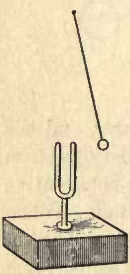


Fig. 153

If a mounted tuning fork (Fig. 153) is sounded, and a light ball of pith or ivory, suspended by a thread, is brought in contact with one of the prongs at the back, it will be briskly thrown away by the energetic vibrations of the fork.

Partly fill a glass goblet with water, and produce a musical note by drawing a bow across its edge. The tremors of the glass will throw the surface of the water into violent agitation in four sectors, with intermediate regions of relative repose. This agitation disappears when the sound ceases.

A glass tube, four or five feet long, may be made to emit a musical sound by grasping it by the middle and briskly rubbing one end with a cloth moistened with water. The vibrations are longitudinal, and may be so energetic as to break the tube into many narrow rings.

Experiments like these show that the sources of sound are bodies in a state of vibration.

180. Media for Transmitting Sound. — Suspend a small electric bell in a bell jar on the air pump table (Fig. 154). When the air is exhausted, the bell is nearly inaudible. Sound does not travel through a vacuum.

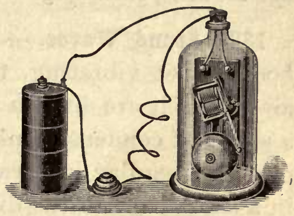


Fig. 154

Fasten the stem of a tuning fork to the middle of a thin disk of wood. Set the fork vibrating, and hold it with the disk resting on the surface of water in a tumbler, standing on a table. The sound, which is scarcely audible when there is no disk attached to the fork, is now distinctly heard as if coming from the table.

Hold one end of a long, slender wooden rod against a door, and rest the stem of a vibrating fork against the other end. The sound will be greatly intensified, and will come from the door as the apparent source.

Press down on a table a handful of putty or dough, and insert in it the stem of a vibrating fork; the vibrations will not be conveyed to the table to an appreciable extent.

Only elastic media transmit sound, and some transmit better than others.

181. Transmission of Sound to the Ear. — Any uninterrupted series of elastic bodies will transmit sound to the ear, be they solid, liquid, or gaseous.

A bell struck under water sounds painfully loud if the ear of the listener is also under water. A diver under water can hear voices in the air. By placing the ear against the steel rail of a railway, two sounds may be heard, if the rail is struck some distance away: a louder one through the rails and then another through the air. The faint scratching of a pin on the end of a long stick of timber, or the ticking of a watch held against it, may be heard very distinctly if the ear is applied to the other end.

The earth conducts sound so well that the stepping of a horse may be heard by applying the ear to the ground. This is understood by the Indians. The firing of a cannon at least 200 miles away may be heard in the same way. The report of a mine blast reaches a listener sooner through the earth than through the air.

The great eruption of Krakatoa in 1883 gave rise to gigantic sound waves, which produced at a distance of 2000 miles a report like the firing of heavy guns.

182. Sound Waves. — When a tuning fork or similar body is set vibrating, the disturbances produced in the air about it are known as *sound waves.* They consist of a series of condensations and rarefactions succeeding each other at regular intervals. Each particle of air vibrates in a short path in the direction of the sound transmission. Its vibrations are *longitudinal* as distinguished from the *transverse* vibrations in water waves.

183. Motion of the Particles of a Wave. — The motion of the particles of the medium conveying sound is distinct from the motion of the sound wave. A sound wave is composed of a condensation followed by a rarefaction. In the former the particles have a forward motion in the direction in which the sound is traveling; in the latter they have a backward motion, while at the same time both condensation and rarefaction travel steadily forward.

The independence of the two motions is aptly illustrated by a field of grain across which waves excited by the wind are coursing. Each stalk of grain is securely anchored to the ground, while the wave sweeps onward. The heads of grain in front of the crest are rising, while all those behind the crest and extending to the bottom of the trough are falling. They all sweep forward and backward, not *simultaneously*, but *in succession*, while the wave itself travels continuously forward.

III. VELOCITY OF SOUND

184. Velocity in Air. — In 1822 a scientific commission in France made experiments to ascertain the velocity of sound in air. Their method was to divide into two parties at stations some distance apart, and to determine

the interval between the observed flash and the report of a cannon fired alternately at the two stations. The mean of an even number of measurements eliminates very nearly the effect of the wind. The final result was 331 m. per second at 0° C. The defect of the method is that the perception of sound and of light are not equally quick, and they vary with different persons.

In 1871 Stone at Cape Town measured the velocity of sound by stationing two observers three miles apart to give signals by electricity on hearing the report of a cannon. The interval between these signals was the time required for the sound to travel the intervening three miles. This method makes use of the sense of hearing only. After correcting as far as possible for all sources of error, the value obtained was 332.4 m. or 1090.5 ft. per second at 0° C. Sound travels faster at a higher temperature. At 20° C. (68° F.) the velocity is about 1130 ft. per second. The correction for temperature is 0.6 m., or nearly 2 ft., per degree C.

185. Velocity in Water. — In 1827 Colladon and Sturm, by a series of measurements in Lake Geneva, found that sound travels in water at the rate of 1435 m. per second at a mean temperature of 8.1° C. They measured with much care the time required for the sound of a bell struck under water to travel through the lake between two boats anchored at a distance apart of 13,487 m. It was 9.4 seconds.

A system of transmitting signals through water by means of submerged bells is in use by vessels at sea and for offshore stations. Special telephone receivers have been devised to operate under water and to respond to these sound signals. Indeed, the vessel itself acts as a sounding board and as a very good receiver.

186. Velocity in Solids. — The velocity of sound in solids is in general greater than in liquids on account of their high elasticity as compared with their density. The velocity in iron is 5127 m. per second; in glass 5026 m. per second; but in lead it is only 1228 m. per second, at a temperature in each case of 0° C.

Questions and Problems

1. Why do the timers in a 200-yd. dash start their stop watches by the flash of the pistol rather than by the report?

2. If the flash of a gun is seen 3 sec. before the report is heard, how far is the gun from the observer, the temperature being 20° C.?

3. The interval between seeing a flash of lightning and hearing the thunder was 5 sec.; the temperature was 25° C. How far away was the lightning discharge?

4. Signals given by a gun 2 mi. away would be how much in error when the temperature is 20° C. and the wind is blowing 10 mi. an hour in the direction from the listener to the gun?

5. A man sets his watch by a steam whistle which blows at 12 o'clock. The whistle is 1.5 mi. away and the temperature 15° C. How many seconds will the watch be in error?

6. A ball fired at a target was heard to strike after an interval of 8 sec. The distance of the target was 1 mi. and the temperature of the air 20° C. What was the mean velocity of the ball?

7. The distance between two points on a straight stretch of railway is 2565 m. An observer listens at one of these points and a blow is struck on the rails at the other. If the temperature is 0° C., what is the interval between the arrival of the two sounds, one through the rails and the other through the air?

8. A man watching for the report of a signal gun saw the flash 2 sec. before he heard the report. If the temperature was 0° C. and the distance of the signal gun was 2225 ft., what was the velocity of the wind?

9. A shell fired at a target, distance half a mile, was heard to strike it 5 sec. after leaving the gun. What was the average speed of the bullet, the temperature of the air being 20° C.?

IV. REFLECTION OF SOUND

187. Echoes.—*An echo is the repetition of a sound by reflection from some distant surface.* A clear echo requires a vertical reflecting surface, the dimensions of which are large compared to the wave length of the sound. A cliff, a wooded hill, or the broad side of a large building may serve as the reflecting surface. Its inequalities must be small compared to the length of the incident sound waves; otherwise, the sound is diffused in all directions. A loud sound in front of a tall cliff an eighth of a mile away will be returned distinctly after about a second and a sixth. If the reflecting surface is nearer than about fifty feet, the reflected sound tends to strengthen the original one, as illustrated by the greater distinctness of sounds indoors than in the open air. In large rooms where the echoes produce a confusion of sounds the trouble may be diminished by adopting some method to prevent regular reflection, such as the hanging of draperies.

188. Multiple Echoes.—Parallel reflecting surfaces at a suitable distance produce *multiple echoes*, as parallel mirrors produce multiple images (§ 241). The circular baptistry at Pisa and its spherical dome prolong a sound for ten or more seconds by successive reflections; the effect is made more conspicuous by the good reflecting surface of polished marble. Extraordinary echoes sometimes occur between the parallel walls of deep cañons.

189. Aërial Echoes.—Whenever the medium transmitting sound changes suddenly in density, a part of the energy is transmitted and a part reflected. The intensity of the reflected system is the greater the greater the difference in the densities of the two media. A dry sail

reflects a part of the sound and transmits a part; when wet it becomes a better reflector and is almost impervious to sound.

Aërial echoes are accounted for by sudden changes of density in the air. Air, almost perfectly transparent to light, may be very opaque to sound. When for any reason the atmosphere becomes unstable, vertical currents and vertical banks of air of different densities are formed. The sound transmitted by one bank is in part reflected by the next, the successive reflections giving rise to a curious prolonging of a short sound. Thus, the sound of a gun or of a whistle is then heard apparently rolling away to a great distance with decreasing loudness.

190. Whispering Gallery. — Let a watch be hung a few inches in front of a large concave reflector (Fig. 155). A place may be found for the ear at some distance in front, as at E, where the ticking of the watch may be heard with great distinctness. The sound waves, after reflection from the concave surface, converge to a point at E.

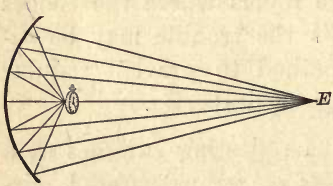


Fig. 155

The action of the ear trumpet depends on the reflection of sound from curved surfaces; the sides of the bell-shaped mouth reflect the sound into the tube which conveys it to the ear.

An interesting case of the reflection of sound occurs in the *whispering gallery*, where a faint sound produced at one point of a very large room is distinctly heard at some distant point, but is inaudible at points between. It requires curved walls which act as reflectors to concentrate the waves at a point. Low whispers on one side of the dome of St. Paul's in London are distinctly audible on the opposite side.

V. RESONANCE

191. Forced Vibrations. — A body is often compelled to surrender its natural period of vibration, and to vibrate with more or less accuracy in a manner imposed on it by an external periodic force. Its vibrations are then said to be *forced.*

Huyghens discovered that two clocks, adjusted to slightly different rates, kept time together when they stood on the same shelf. The two prongs of a tuning fork, with slightly different natural periods on account of unavoidable differences, mutually compel each other to adopt a common frequency. These two cases are examples of mutual control, and the vibrations of both members of each pair are forced.

The sounding board of a piano and the membrane of a banjo are forced into vibration by the strings stretched over them. The top of a wooden table may be forced into vibration by pressing against it the stem of a vibrating tuning fork. The vibrations of the table are forced and it will respond to a fork of any period.

192. Sympathetic Vibrations. — Place two mounted tuning forks, tuned to exact unison, near each other on a table. Keep one of them in vibration for a few seconds and then stop it; the other one will be heard to sound.

In the case of these forks, the pulses in the air reach the second fork at intervals corresponding to its natural vibration period and the effect is cumulative. The experiment illustrates *sympathetic vibrations* in bodies having the same natural period. If the forks differ in period, the impulses from the first do not produce cumulative effects on the second, and it will fail to respond.

Suspend a heavy weight by a rope and tie to it a thread. The weight may be set swinging by pulling gently on the thread, releasing it, and pulling again repeatedly when the weight is moving in the direction of the pull.

Suspend two heavy pendulums on knife-edges on the same stand, and carefully adjust them to swing in the same period. If then one is set swinging, it will cause the other one to swing, and will give up to it nearly all its own motion.

When the wires of a piano are released by pressing the loud pedal, a note sung near it will be echoed by the wire which gives a tone of the same pitch.

A number of years ago a supension bridge of Manchester in England was destroyed by its vibrations reaching an amplitude beyond the limit of safety. The cause was the regular tread of troops keeping time with what proved to be the natural rate of vibration of the bridge. Since then the custom has always been observed of breaking step when bodies of troops cross a bridge.

193. Resonance. — *Resonance is the reënforcement of sound by the union of direct and reflected sound waves.*

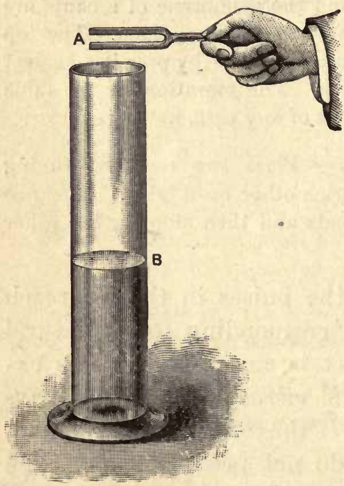


Fig. 156

Hold a vibrating tuning fork over the mouth of a cylindrical jar (Fig. 156). Change the length of the air column by pouring in water slowly. The sound will increase in loudness until a certain length is reached, after which it becomes weaker. A fork of different pitch will require a different length of air column to reënforce its sound.

The "sound of the sea" heard when a sea shell is held to the ear is a case of resonance. The mass of air in the shell has a vibration rate of its own, and it amplifies any faint sound of the same period. A vase with a long neck, or even a teacup, will also exhibit resonance.

The box on which a tuning fork is mounted (Fig. 157) is a resonator, designed to increase the volume of sound. The air within the body of a violin and all instruments of like character acts as a

resonator. The air in the mouth, the larynx, and the nasal passages is a resonator; the length and volume of this body of air can be changed at pleasure so as to reënforce sounds of different pitch.

194. The Helmholtz Resonator. — The resonator devised by Helmholtz is spherical in form, with two short tubes on opposite sides (Fig. 158). The larger opening *A* is the mouth of the resonator; the smaller one *B* fits in the ear. These resonators are made of thin brass or of glass, and their pitch is determined by their size. When one of them is held to the ear, it strongly reënforces any sound of its own rate of vibration, but is silent to others.

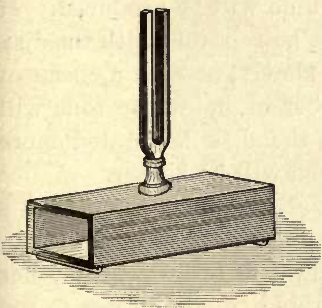


Fig. 157

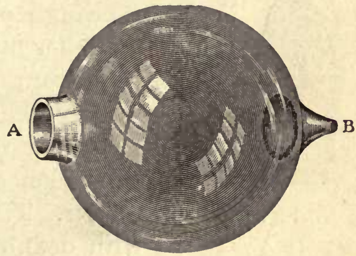


Fig. 158

VI. CHARACTERISTICS OF MUSICAL SOUNDS

195. Musical Sounds. — Sounds are said to be *musical* when they are pleasant to the ear. They are caused by regular periodic vibrations. A *noise* is a disagreeable sound, either because the vibrations producing it are not periodic, or because it is a mixture of discordant elements, like the clapping of the hands.

Musical sounds have three distinguishing characteristics: *pitch*, *loudness*, and *quality*.

196. Pitch. — Mount on the axle of a whirling machine (Fig. 159), or on the armature of a small electric motor, a cardboard or metal disk D with a series of equidistant holes in a circle near its edge. While the disk is rotating rapidly, blow a stream of air through a small tube against the circle of holes. A distinct musical tone will be produced. If the experiment be repeated with the disk rotating more slowly, or with a circle of a smaller number of holes, the tone will be lower; if the disk is rotated more rapidly, the tone will be higher.

Fig. 159

The air passes through the holes in a succession of puffs producing waves in the air. These waves follow one another with definite rapidity, giving rise to the characteristic of sound called *pitch*. We conclude that *the pitch of a musical sound depends only upon the number of pulses which reach the ear per second.* To Galileo belongs the credit of first pointing out the relation of pitch to frequency of vibration. He illustrated it by drawing the edge of a card over the milled edge of a coin.

197. Relation between Pitch, Wave Length, and Velocity. — If a tuning fork makes 256 vibrations per second, and in that time a sound travels in air, at 20° C., a distance of 344 m., then the first wave will be 344 m. from the fork when it completes its 256th vibration. Hence, in 344 m., there will be 256 waves, and the length of each will be $\frac{344}{256}$ m., or 1.344 m. In general, then,

$$\textit{wave length} = \frac{\textit{velocity}}{\textit{frequency}},$$

Hermann von Helmholtz (1821–1894) was born at Potsdam. He received a medical education at Berlin and planned to be a specialist in diseases of the eye, ear, and throat. His studies soon revealed to him the need of a knowledge of physics and mathematics. To these subjects he gave his earnest attention and soon became one of the greatest physicists and mathematicians of the nineteenth century. He made important contributions to all departments of physical science. He is the author of an important work on acoustics and is celebrated for his discoveries in this field. But perhaps his most useful contribution is that of the ophthalmoscope, an instrument of inestimable value to the oculist in examining the interior of the eye.

or in symbols, $l = \frac{v}{n}$, $v = nl$, and $n = \frac{v}{l}$. . (Equation 31)

198. Loudness. — The *loudness* of a sound depends on the intensity of the vibrations transmitted to the ear. The energy of the vibrations is proportional to the square of their amplitude; but since it is obviously impracticable to express a sensation in terms of a mathematical formula, it is sufficient to say that the loudness of a sound increases with the amplitude of vibration.

As regards distance, geometrical considerations would go to show that the energy of sound waves in the open decreases as the square of the distance increases, but the actual decrease in the intensity of sound is even greater than this. The energy of sound waves is gradually dissipated by conversion into heat through friction and viscosity.

199. Quality. — Two notes of the same pitch and loudness, such as those of a piano and a violin, are yet clearly distinguishable by the ear. This distinction is expressed by the term *quality* or *timbre*. Helmholtz demonstrated that the quality of a note is determined by the presence of tones of higher pitch, whose frequencies are simple multiples of that of the fundamental or lowest tone. These are known as *overtones*.

The quality of sounds differs because of the series of overtones present in each case. Voices differ for this reason. Violins differ in sweetness of tone because the sounding boards of some bring out overtones different from those of others. Even the untrained ear can readily appreciate differences in the character of the music produced by a flute and a cornet. Voice culture consists in training and developing the vocal organs and resonance

cavities, to the end that purer overtones may be secured, and greater richness may by this means be imparted to the voice.

VII. INTERFERENCE AND BEATS

200. Interference. — Hold a vibrating tuning fork over a cylindrical jar adjusted as a resonator, and turn the fork on its axis until a position of minimum loudness is found. In this position cover one prong with a pasteboard tube without touching (Fig. 160). The sound will be restored to nearly maximum loudness, because the paper cylinder cuts off the set of waves from the covered prong.

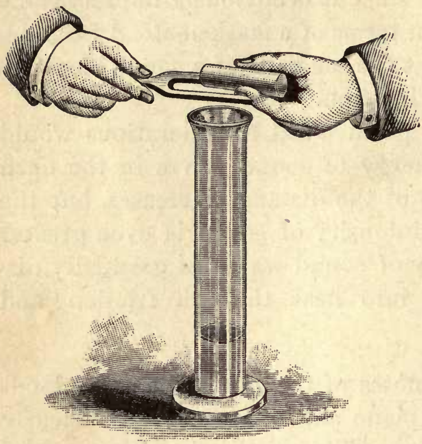


Fig. 160

It is well known that the loudness of the sound of a vibrating fork held freely in the hand near the ear, and turned on its stem, exhibits marked variations. In four positions the sound is nearly inaudible. Let A, B (Fig. 161) be the ends of the two prongs. They vibrate with the same frequency, but in opposite directions, as indicated by the arrows. When the two approach each other, a condensation is produced between them, and at the same

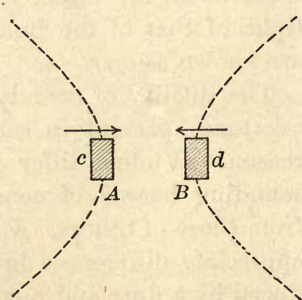


Fig. 161

time rarefactions start from the backs at *c* and *d*. The condensations and rarefactions meet along the dotted lines of equilibrium, where partial extinction occurs, because a rarefaction nearly annuls a condensation. When the fork is held over the resonance jar so that one of these lines of interference runs into the jar, the paper cylinder cuts off one set of waves, and leaves the other to be reënforced by the air in the jar.

Interference is the superposition of two similar sets of waves traversing the medium at the same time. One of the two sets of similar waves may be direct and the other reflected. If two sets of sound waves of equal length and amplitude meet in opposite phases, the condensation of one corresponding with the rarefaction of the other, the sound at the place of meeting is extinguished by interference.

201. Beats. — Place near each other two large tuning forks of the same pitch and mounted on resonance boxes. When both are set vibrating, the sound is smooth, as if only one fork were sounding. Stick a small piece of wax to a prong of one fork; this load increases its periodic time of vibration, and the sound given by the two is now pulsating or throbbing.

Mount two organ pipes of the same pitch on a bellows, and sound them together. If they are open pipes, a card gradually slipped over the open end of one of them will change its pitch enough to bring out strong pulsations.

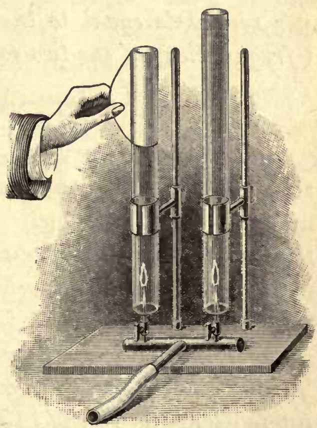


Fig. 162

With glass tubes and jet tubes set up the apparatus of Fig. 162. One tube is fitted with a paper slider so that its length may be varied. When the gas flame is turned down to the proper size, the

tube gives a continuous sound known as a "singing flame." By making the tubes the same length, they may be made to yield the same note, the combined sound being smooth and steady. Now change the position of the slider, and the sound will throb and pulsate in a disagreeable manner.

These experiments illustrate the interference of two sets of sound waves of slightly different period. *The outbursts of sound, followed by short intervals of comparative silence, are called beats.*

202. Number of Beats. — If two sounds are produced by forks, for example, making 100 and 110 vibrations per second respectively, then in each second the latter fork gains ten vibrations on the former. There must be ten times during each second when they are vibrating in the same phase, and ten times in opposite phase. Hence, interference of sound must occur ten times a second, and ten beats are produced. Therefore, the *number of beats per second is equal to the difference of the vibration rates (frequencies) of the two sounds.*

VIII. MUSICAL SCALES

203. Musical Intervals. — A musical interval is the relation between two notes expressed as the ratio of their frequencies of vibration. Many of these intervals have names in music. When the ratio is 1, the interval is called *unison;* 2, an *octave;* $\frac{3}{2}$, a *fifth;* $\frac{4}{3}$, a *fourth;* etc. Any three notes whose frequencies are as $4:5:6$ form a *major triad*, and alone or together with the octave of the lowest note, a *major chord.* Any three notes whose frequencies are as $10:12:15$ form a *minor triad*, and alone or with the octave of the lowest, a *minor chord.*

Mount the disk of Fig. 163 on the whirling table of Fig. 159. The disk is perforated with four circles of equidistant holes, number-

ing 24, 30, 36, and 48 respectively. These are in the relation of 4, 5, 6, 8. Rotate with uniform speed, and beginning with the inner circle, blow a stream of air against each row of holes in succession. The tones produced will be recognized as *do, mi, sol, do′*, forming a major chord. If now the speed of rotation be increased, each note will rise in pitch, but the musical sequence will remain the same.

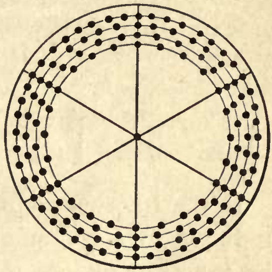


Fig. 163

It will be seen from the foregoing relations that harmonious musical intervals consist of very simple vibration ratios.

204. The Major Diatonic Scale. — A *musical scale* is a succession of notes by which musical composition ascends from one note, called the *keynote*, to its octave. This last note in one scale is regarded as the keynote of another series of eight notes with the same succession of intervals. In this way the series is extended until the limit of pitch established in music is reached.

The common succession of eight notes, called the *major diatonic scale*, was adopted about three hundred and fifty years ago. The octave beginning with middle C is written

$$c' \quad d' \quad e' \quad f' \quad g' \quad a' \quad b' \quad c''$$

The three major triads for the keynote of C are :

$$\left.\begin{array}{l} c' : e' : g' \\ g' : b' : d'' \\ f' : a' : c'' \end{array}\right\} :: 4 : 5 : 6$$

The frequency universally assigned to c' in physics is 256. It is convenient because it is a power of 2, and it is practically that of the "middle C" of the piano. If c' is due to 256, or m, vibrations per second, the frequency

of the other notes of the diatonic scale may be found by proportion from the three triads above; they are as follows:

256	288	320	$341\frac{1}{3}$	384	$426\frac{2}{3}$	480	512
c'	d'	e'	f'	g'	a'	b'	c''
do	*re*	*mi*	*fa*	*sol*	*la*	*si*	*do*
m	$\frac{9}{8}m$	$\frac{5}{4}m$	$\frac{4}{3}m$	$\frac{3}{2}m$	$\frac{5}{3}m$	$\frac{15}{8}m$	$2m$

If the fractions representing the relative frequencies be reduced to a common denominator, the numerators may be taken to denote the relative frequencies of the eight notes of the scale. They are

$$24 \quad 27 \quad 30 \quad 32 \quad 36 \quad 40 \quad 45 \quad 48$$

An examination of these numbers will show that there are only three intervals *from any note to the next higher.* They are $\frac{9}{8}$, a major tone; $\frac{10}{9}$, a minor tone; and $\frac{16}{15}$, a half tone. The order is $\frac{9}{8}$, $\frac{10}{9}$, $\frac{16}{15}$, $\frac{9}{8}$, $\frac{10}{9}$, $\frac{9}{8}$, $\frac{16}{15}$.

205. The Tempered Scale. — If C were always the keynote, the diatonic scale would be sufficient for all purposes except for minor chords; but if some other note be chosen for the keynote, in order to maintain the same order of intervals, new and intermediate notes will have to be introduced. For example, let D be chosen for the keynote, then the next note will be $288 \times \frac{9}{8} = 324$ vibrations, a number differing slightly from E. Again, $324 \times \frac{10}{9} = 360$, a note differing widely from any note in the series. In like manner, if other notes are taken as keynotes, and a scale is built up with the order of intervals of the diatonic scale, many more new notes will be needed. This interpolation of notes for both the major and minor scales would increase the number in the octave to seventy-two.

In instruments with fixed keys such a number is unmanageable, and it becomes necessary to reduce the number by changing the value of the intervals. Such a modification of the notes is called *tempering.* Of the several methods proposed by musicians, that of *equal temperament* is the one generally adopted. It makes all the intervals from note to note equal, interpolates one note in each whole tone of the diatonic scale, and thus reduces the number of intervals in the octave to twelve. The only accurately tuned interval in this scale is the octave; all the others are more or less modified. The following table shows the differences between the diatonic and the equally tempered scales:

	c'	d'	e'	f'	g'	a'	b'	c''
Diatonic . .	256	288	320	341.3	384	426.7	480	512
Tempered . .	256	287.3	322.5	341.7	383.6	430.5	483.3	512

Fig. 164

Figure 164 illustrates the scale of C on the staff and the keyboard.

206. Limits of Pitch. — The *international pitch*, now in general use in Europe and America, assigns to a' the vibration frequency of 435. In the modern piano of seven octaves the bass A has a frequency of about 27.5, the highest A, 3480.

The gravest note of the organ is the C of 16 vibrations

per second; the highest note is the same as the highest note of the piano, the third octave above a', with a frequency of 3480.

The limits of hearing far exceed those of music. The range of audible sounds is about eleven octaves, or from the C of 16 vibrations to that of 32,768, though many persons of good hearing perceive nothing above a frequency of 16,384, an octave lower.

Questions and Problems

1. Why is the pitch of the sounds given by a phonograph raised by increasing the speed of the cylinder or the disk containing the record?

2. A megaphone or a speaking tube makes a sound louder at a distance. Explain why.

3. The teeth of a circular saw give a note of high pitch when they first strike a plank. Why does the pitch fall when the plank is pushed further against the saw?

4. Miners entombed by a fall of rock or by an explosion have signaled by taps on a pipe or by pounding on the rock. How does the sound reach the surface?

5. Two Rookwood vases in the form of pitchers with slender necks give musical sounds when one blows across their mouth. Why does the larger one give a note of lower pitch than the smaller?

6. What note is made by three times as many vibrations as c' (middle C)?

7. If c' is due to 256 vibrations per second, what is the frequency of g'' in the next octave?

8. What is the wave length of g' when sound travels 1130 feet per second?

9. If c' has 264 vibrations per second, how many has a'?

10. When sound travels 1120 ft. per second, the wave length of the note given by a fork was 3.5 ft. What was the pitch of the fork?

IX. VIBRATION OF STRINGS

207. Manner of Vibration. — When strings are used to produce sound, they are fastened at their ends, stretched to the proper tension, and are made to vibrate transversely by drawing a bow across them, striking with a light hammer as in the piano, or plucking with the fingers as in the banjo, guitar, or harp.

208. The Sonometer. — The *sonometer* is an instrument for the study of the laws governing the vibration of strings. It consists of a thin wooden box, across which is stretched a violin string or a thin piano wire (Fig. 165).

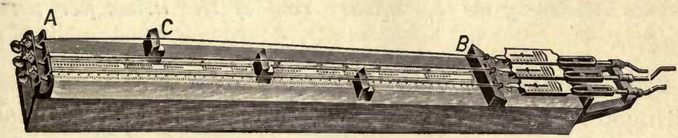


Fig. 165

The wires pass over fixed bridges, *A* and *B*, near the ends, and are stretched by tension balances at one end. They may be shortened by movable bridges *C*, sliding along scales under the wires.

209. Laws of Strings. — Stretch two similar wires on the sonometer and tune to unison by varying the tension. Shorten one of them by moving the bridge *C* to $\frac{8}{9}$, $\frac{4}{5}$, $\frac{3}{4}$, $\frac{2}{3}$, etc. The successive intervals between the notes given by the two wires will be $\frac{9}{8}$, $\frac{5}{4}$, $\frac{4}{3}$, $\frac{3}{2}$, etc. The notes given by the wire of variable length are those of the major diatonic scale. Hence,

The frequency of vibration for a given tension varies inversely as the length.

Starting with a given tension and the strings or wires in unison, increase the stretching force on one of them four times; it will now

give the *octave* of the other with twice the frequency. Increase the tension nine times; it will give the octave plus the fifth, or the *twelfth*, above the other with three times the frequency. These statements may be verified by dividing the comparison wire by a bridge into halves and thirds, so as to put it in unison with the wire of variable tension. Hence,

When the length is constant, the frequency varies as the square root of the tension.

Stretch equally two wires differing in diameter and material, that is, in mass per unit length. Bring them to unison with the movable bridge. The ratio of their lengths will be inversely as that of the square roots of the masses per unit length. Hence,

The length and tension being constant, the frequency varies inversely as the square root of the mass per unit length.

210. Applications. — In the piano, violin, harp, and other stringed instruments, the pitch of each string is determined partly by its length, partly by its tension, and partly by its size or the mass of fine wire wrapped around it. The tuning is done by varying the tension.

211. Fundamental Tone. — Fasten one end of a silk cord about a meter long to one prong of a large tuning fork, and wrap the other end around a wooden pin inserted in an upright bar in such a way that tension can be applied to the cord by turning the pin. Set the fork vibrating, and adjust the tension until the cord vibrates as a whole (Fig. 166). Arranged in this way, the frequency of the fork is double that of the cord.

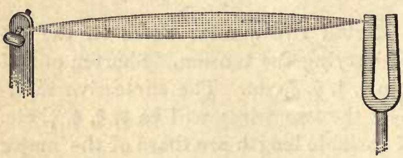


Fig. 166

The experiment shows the way a string or wire vibrates when giving its lowest or *fundamental tone.* A body

yields its fundamental tone when vibrating as a whole, or in the smallest number of segments possible.

212. Nodes and Segments. — With a silk cord about 2 m. long, and mounted as in the last experiment, adjust the tension until the cord vibrates in a number of parts, giving the appearance of a succession of spindles of equal length (Fig. 167). The frequency of the fork is twice that of each spindle.

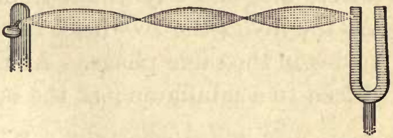


Fig. 167

Stretch a wire on a sonometer with a thin slip of cork strung on it. Place the cork at one third, one fourth, one fifth, or one sixth part of the wire from one end; touch it lightly, and bow the shorter portion of the wire. The wire will vibrate in equal segments (Fig. 168). The division into segments may be made more conspicuous by placing on the wire, before bowing it, narrow V-shaped pieces of paper, or riders. If, for example, the cork is placed at one fourth the length of the wire, the paper riders should be in the middle, and at one fourth the length from the other end, and at points midway between these. When the wire is deftly bowed, the riders at the fourths will remain seated, and the intermediate ones will be thrown off. The latter mark points of maximum, and the former those of minimum vibration.

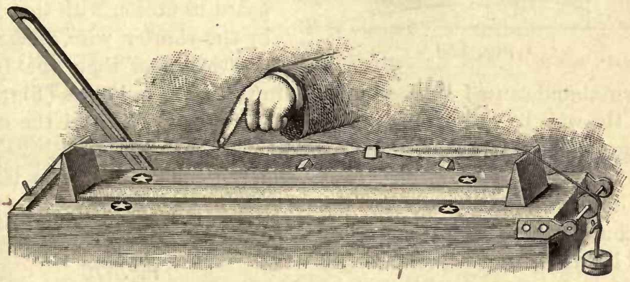


Fig. 168

The ends of the wire and the intermediate points of least motion are called *nodes;* the vibrating portions be-

tween the nodes are *loops* or *segments;* and the middle points of the loops are called *antinodes.* The last two experiments illustrate what are known as *stationary waves.* They result from the interference of the direct system of waves and those reflected from the fixed end of the wire. At the nodes the two meet in opposite phase ; at the antinodes in the same phase. At the former the motion is reduced to a minimum; at the latter it rises to a maximum.

213. Overtones in Strings. — Stretch two similar wires on the sonometer and tune to unison; then place a movable bridge at the middle of one of them. Set the longer wire in vibration by plucking or bowing it near one end. The tone most distinctly heard is its fundamental. Touch it lightly at its middle point; instead of stopping the sound, a tone is now heard in unison with that given by the shorter wire, that is, an octave higher than the fundamental and caused by the longer wire vibrating in halves (Fig. 169). If the wire be again plucked, both the fundamental and the octave may be heard together.

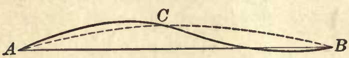


Fig. 169

Touching the wire one third from the end brings out a tone in unison with that given by the second wire reduced to one third its length by the movable bridge, that is, it yields a tone of three times the frequency, or an octave and a fifth higher than the fundamental. Figure 170 illustrates the manner in which the wire is vibrating.

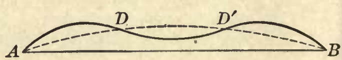


Fig. 170

The experiment shows that a wire may vibrate not only as a whole but at the same time in parts, yielding a complex note. The tones produced by a body vibrating in parts are called *overtones* or *partial tones.*

214. Harmonics. — If the frequency of vibration of the overtone is an exact multiple of the fundamental, it is called an *harmonic partial* or simply an *harmonic.* In

strings the overtones are usually harmonics, but in vibrating plates and membranes they are not.

The harmonics are named first, second, third, etc., in the order of their vibration frequency. The frequency of any particular harmonic is found by multiplying that of the fundamental by a number one greater than the number of the harmonic. For example, the frequency of the first harmonic of c' of 256 vibrations per second is $256 \times 2 = 512$; that of the second is $256 \times 3 = 768$, etc.

X. VIBRATION OF AIR IN PIPES

215. Air as a Source of Sound. — In the use of the resonator we saw that air may be thrown into vibration when it is confined in tubes or globes, and that it thus becomes the source of sound. Such a body of air may be set vibrating in two ways: by a vibrating tongue or reed, as in the clarinet (Fig. 171), the fish horn, etc., or by a

Fig. 171

stream of air striking against the edge of an opening in the tube, as in the whistle, the flute (Fig. 172), the

Fig. 172

organ pipe, etc. In several pipe or wind instruments (1) the lips of the player act as reeds, as in the trumpet, trombone (Fig. 173), the French horn, and the cornet.

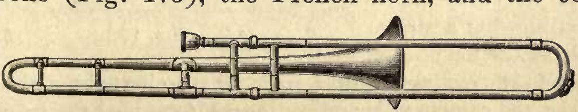


Fig. 173

Wind instruments may be classed as open or stopped pipes, according as the end remote from the mouthpiece is open or closed.

216. Fundamental of a Closed Pipe. — Let the tall jar of Fig. 174 be slowly filled with water until it responds strongly to a c' fork, for example. The length of the column of air will be about 13 in. or one fourth of the wave length of the note.

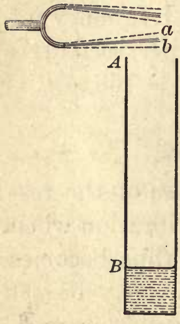


Fig. 174

When the prong at a moves to b, it makes half a vibration, and generates half a sound wave. It sends a condensed pulse down the tube AB, and this pulse is reflected from the water at the bottom. Now, if AB is one fourth a wave length, the distance down and back is one half a wave length, and the pulse will return to A at the instant when the prong begins to move from b back to a, and to send a rarefaction down AB. This in turn will run down the tube and back, as the prong completes its vibration; the co-vibration is then repeated indefinitely, the tube responds to the fork, and its length is one quarter of the wave length. Hence,

The fundamental of a closed pipe is a note whose wave length is four times the length of the pipe.

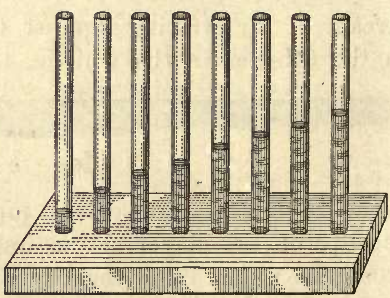


Fig. 175

217. Laws for Columns of Air. — Set vertically in a wooden base eight glass tubes each about 25 cm. long and 2 cm. in diameter (Fig. 175). Pour in them melted paraffin to close the bottom. A musical note may be produced by blowing a stream of air across the top of each tube. From the confused flutter made by the air striking the edge of the tube, the column of air selects for reënforcement the frequency

corresponding to its own rate. Hence the pitch may be varied by pouring in water. Adjust all the tubes with water until they give the eight notes of the major diatonic scale. The measured lengths of the columns of air will be found to be nearly as 1, $\frac{8}{9}$, $\frac{4}{5}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{3}{5}$, $\frac{8}{15}$, $\frac{1}{2}$. The notes emitted have the frequencies 1, $\frac{9}{8}$, $\frac{5}{4}$, $\frac{4}{3}$, $\frac{3}{2}$, $\frac{5}{3}$, $\frac{15}{8}$, 2 (§ 204). Hence,

The frequency of a vibrating column of air is inversely as its length.

This is the principle employed in playing the trombone.

Blow gently across the end of an open tube 30 cm. long and about 2 cm. in diameter and note the pitch. Take another tube of the same diameter and 15 cm. long; stop one end by pressing it against the palm of the hand, and sound it by blowing across the open end. The pitch of the closed pipe will be the same as that of the open one. The experiment may be varied by comparing the notes obtained by the shorter pipe when open and when closed at one end; the former will be an octave higher than the latter. Hence,

For the same frequency, the open pipe is twice the length of the stopped one.

The length of the open pipe is, therefore, half the wave length of the fundamental note in air.

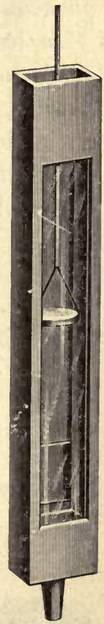


Fig. 176

218. State of the Air in a Sounding Pipe. — Employing an open organ pipe, preferably with one glass side (Fig. 176), lower into it a miniature tambourine about 3 cm. in diameter and covered with fine sand, while the pipe is sounding its fundamental note. The sand will be agitated most at the ends of the pipe and very little at the middle. There is, therefore, a *node* at the middle of an open pipe. A node is a place of least motion and greatest change of density; an antinode is a place of greatest motion and least change of density. The closed end of a pipe is necessarily a node, and the open end an antinode. Hence,

In an open pipe, for the fundamental tone, there is a node at the middle and an antinode at each end; in

the stopped pipe, there is a node at the closed end and an antinode at the other end.

219. Overtones in Pipes. — Blow across the open end of a glass tube about 75 cm. long and 2 cm. in diameter. A variety of tones of higher pitch than the fundamental may be obtained by varying the force of the stream of air.

These tones of higher pitch than the fundamental are *overtones;* they are caused by the column of air vibrating in parts or segments with intervening nodes.

Open pipes give the complete series of overtones, with frequencies 2, 3, 4, 5, etc. times that of the fundamental.

In stopped pipes only those overtones are possible whose frequencies are 3, 5, 7, etc. times that of the fundamental. Briefly, the reason is that with a node at one end and an antinode at the other, the column of air can divide into an *odd* number of equal half segments only.

It follows that the notes given by open pipes differ in quality from those of closed pipes.

XI. GRAPHIC AND OPTICAL METHODS

220. Record of Vibrations. — Graphic methods of studying sound are of service in determining the frequency of vibration. Figure 177 shows a practical device for this purpose. A sheet of paper is wrapped around a metal cylinder, and is then smoked with lampblack. A large fork is securely

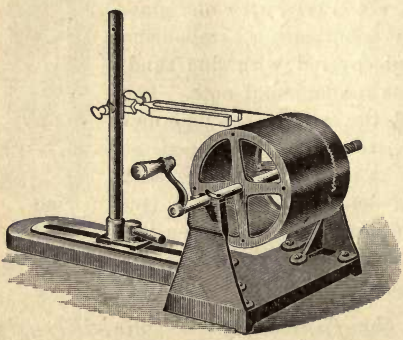


Fig 177

mounted, so that a light style attached to one prong touches the paper lightly. The cylinder is mounted on an axis, one end of which has a screw thread cut in it, so that when the cylinder turns it also moves in the direction of its axis. The beats of a seconds pendulum may be marked on the paper by means of electric sparks between the style and the cylinder. The number of waves between successive marks made by the spark is equal to the frequency of the fork.

221. Manometric Flames. — A square box with mirror faces is mounted so as to turn around a vertical axis (Fig. 178). In front of the revolving mirrors is supported a short cylinder, which is divided into two shallow chambers by a partition of goldbeater's skin or thin rubber. Illuminating gas is admitted to the compartment on the right through the tube with a stopcock, and burns at the small gas jet on the little tube running into this same compartment. The speaking tube is connected to the compartment on the other side of the flexible partition.

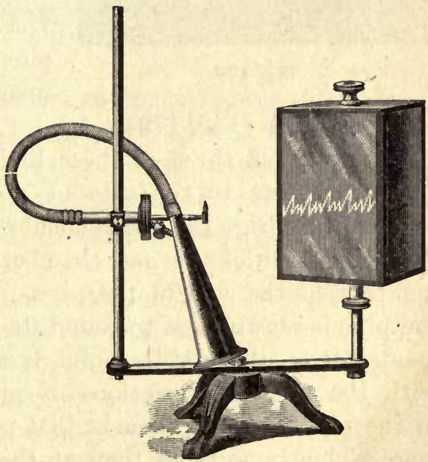


Fig. 178

When the mirrors are turned by twirling with the thumb and finger the milled head at the top, the image

of the gas jet is drawn out into a smooth band of light. Any pure tone at the mouthpiece produces alternate compressions and rarefactions in both chambers separated by the membrane, and these aid and retard the flow of gas to the burner. The flame changes shape and flickers, but its vibrations are too rapid to be seen directly. But if it is examined by reflection from the rotating mirrors, its image is a serrated band (Fig. 179).

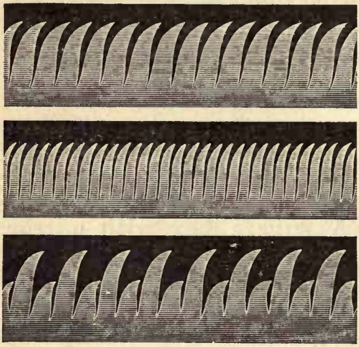


Fig. 179

Koenig fitted three of these little capsules with jets to the side of an open organ pipe (Fig. 180), the membrane on the inner side of the gas chamber forming part of the wall of the pipe. When the pipe is blown so as to sound its fundamental tone, the middle point is a node with the greatest variations of pressure in the pipe, and the flame at that point is more violently agitated than at the other two, giving in the mirrors the top band of Fig. 179. By increasing the air blast, the fundamental is made to give way to the first overtone; the two outside jets then vibrate most strongly, and give the second band in the figure, with twice as many

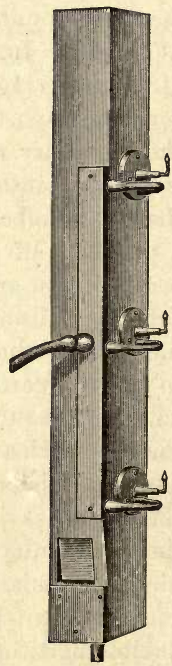


Fig. 180

tongues of flame as in the image for the fundamental. The third band may be obtained by adjusting the air pressure so that both the fundamental and the first overtone are produced at the same time. This same figure may be obtained by singing into the mouthpiece or funnel of Fig. 178 the vowel sound *o* on the note *B*, showing that this vowel sound is composed of a fundamental and its octave.

222. Kundt's Dust Tube. — The division of a resonant pipe into segments may be beautifully shown by means

Fig. 181

of a glass tube about 2 cm. in diameter and 40 cm. long. One end is closed, and a common whistle is attached to the other (Fig. 181). Within the tube is evenly sifted a little dry cork dust, or amorphous silica. When the whistle is blown, the powder is caught up by the moving air at the antinodes, and settles down in small circles at the nodes. At the same time, between the nodes it is divided into thin, airy segments, with vertical divisions, the agitation being sufficient to support the dust in opposition to gravity. The subdivision changes when the blast of air is increased to give overtones.

Questions and Problems

1. Name three ways in which musical sounds may differ.

2. Pianos are made so that the hammers strike the wires near one end and not in the middle. Why?

3. Why does the pitch of the sound made by pouring water into a tall cylindrical jar rise as the jar fills?

4. What effect does a rise of temperature have on the pitch of a given organ pipe? Explain.

5. If the pipes of an organ are correctly tuned at a temperature of 40° F., will they still be in tune at 90° F.? Explain.

6. The tones of three bells form a major triad. One of them gives a note *a* of 220 vibrations per second, and its pitch is between those of the other two. What are the frequencies of the three bells, and what is the note given by the highest?

7. How much must the tension of a violin string be increased to raise its pitch a fifth (§ 203)?

8. If the *E* string of a violin is 40 cm. long, how long must a similar one be to give *G*?

9. The vibration frequency of two similar wires 100 cm. long is 297. How many beats per second will be given by the two wires when one of them is shortened one centimeter?

10. Two c' forks gave 5 beats per second when one of them was weighted with bits of sealing wax. Find the frequency of the weighted fork.

11. What will be the length of a stopped organ pipe to give c' of 256 vibrations per second when the temperature of the air is 20° C?

12. Calculate the length of an open organ pipe whose fundamental tone is one of 32 vibrations per second, and the temperature of the air is 20° C.

13. An open organ pipe sounds c' (256); what notes are its two lowest overtones?

14. What is the frequency of an 8-foot stopped pipe when the velocity of sound is 1120 ft. per second?

15. Two open organ pipes 2 ft. in length are blown with air at a temperature of 15° and 20° C., respectively. How many beats do they give per second?

16. When the temperature of the air is such that the velocity of sound is 1105 ft. per second, what will be the frequency of the fundamental note produced by blowing across one end of a tube 12.75 in. long, the other end being closed? What will be the frequency of its first overtone?

CHAPTER VIII

LIGHT

I. NATURE AND TRANSMISSION OF LIGHT

223. The Ether. — Exhaust the air as far as possible from a glass bell jar. Place a candle on the far side of the jar; it will be seen as clearly before the air has been let into the bell jar as after.

It is obvious that the medium conveying light is not the air and it must be something that exists even in a vacuum. Physicists have agreed to call this medium *the ether.* It exists everywhere, even penetrating between the molecules of ordinary matter. Little is known about its nature and the exact way in which light travels through it, but it is generally agreed that *light is a wave motion in the ether* and that the vibrations are not longitudinal as in sound waves, but *transverse* (§ 174).

The theory that light is a wave motion in the ether was proposed by Huyghens, a Dutch physicist, in 1678; Fresnel, a French physicist, showed that the disturbance must be transverse; and Maxwell modified the theory to the effect that these disturbances are probably not transverse physical movements of the ether, but transverse alterations in its electrical and magnetic conditions.

224. Transparent and Opaque Bodies. — When light falls on a body, a part of it is reflected, a part passes through or is transmitted, and the rest is absorbed. A body is *transparent* when it allows light to pass through it with so little loss that objects can be easily distinguished through it, as glass, air, pure water. *Translucent* bodies

transmit light, but so imperfectly that objects cannot be seen distinctly through them, as horn, oiled paper, very thin sheets of metal or wood. Other bodies, such as blocks of wood or iron, transmit no light, and these are *opaque*. No sharp line of separation between these classes can be drawn; the classification is one of degree. Water when deep enough cuts off all light; the bottom of the deep ocean is dark. Stars which are invisible at the foot of a mountain are often visible at the top.

225. Speed of Light. — Previous to the year 1676 it was believed that light traveled infinitely fast, because no one had found a way to measure so great a velocity. But in that year Roemer, a young Danish astronomer, made the very important discovery that *light travels with finite speed.* Roemer was engaged at the Paris Observatory in observing the eclipses of the inner satellite or moon of the planet Jupiter. At each revolution of the moon *M* (Fig. 182) in its orbit round the planet *J*, it passes into the shadow of the planet and becomes invisible from the earth at *E*, or is eclipsed. By comparing his observations with much earlier recorded ones, Roemer found that the mean interval of time between two successive eclipses was 42.5 hours. From this

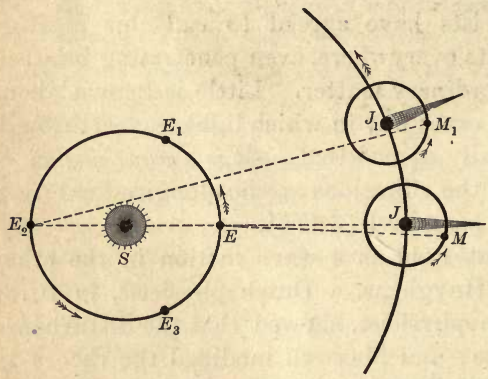
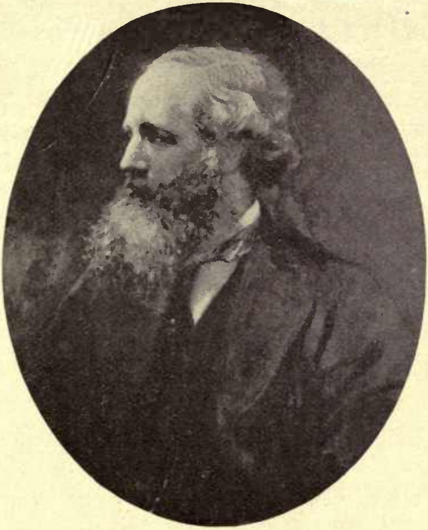


Fig. 182



James Clerk-Maxwell (1831–1879) was a remarkable physicist and mathematician. He was born in Edinburgh and studied in the University of that city. Later he attended the University of Cambridge, graduating from there in 1854. In 1856 he became professor of natural philosophy at Marischal College, Aberdeen, and in 1860 professor of physics and astronomy at King's College, London. In 1871 he was appointed professor of experimental physics in Cambridge. His contributions to the kinetic theory of gases, the theory of heat, dynamics, and the mathematical theory of electricity and magnetism are imperishable monuments to his great genius and wonderful insight into the mysteries of nature.

it was easy to calculate in advance the time at which succeeding eclipses would occur. But when the earth was going directly away from Jupiter, as at E_1, the eclipse interval was found to be longer than anywhere else; and at E_2, across the earth's orbit from Jupiter, each eclipse occurred about 1000 sec. later than the predicted time. To account for this difference Roemer advanced the theory that this interval of 1000 sec. is the time taken by light to pass across the diameter of the earth's orbit. This gave for the speed of light 309 million meters, or 192,000 mi. per second.

Later determinations in our own country by Michelson and Newcomb show that the speed of light is 299,877 km., or 186,337 mi. per second.

226. Direction of Propagation. — Place a sheet-iron cylinder over a strong light, such as a Welsbach gas lamp, in a darkened room. The cylinder should have a small hole opposite the light. Stretch a heavy white thread in the light streaming through the aperture. When the thread is taut it is visible throughout its entire length, but if permitted to sag it becomes invisible.

The experiment shows that *light travels in straight lines.* It will appear later that this is true only when the medium through which light passes has the same physical properties in all directions.

227. Ray, Beam, Pencil. — Light is propagated outward from the luminous source in concentric spherical waves, as sound waves in air are from a sonorous body. *Rays are the radii of these spherical waves*, and they are, therefore, normal (perpendicular) to them. They mark the direction of propagation.

When the source of light is at a great distance, the rays incident on any surface are sensibly parallel. A number of parallel rays form a *beam of light.* For example, in the

case of light from the sun or stars, the distance is so great that the rays are sensibly parallel. Rays of light proceeding outward from a point form a *diverging pencil;* rays proceeding toward a point, a *converging pencil.*

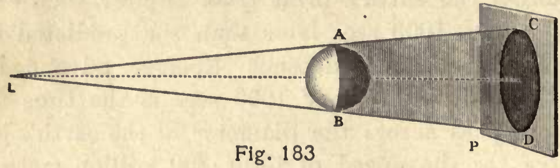


Fig. 183

228. Shadows. — Place a ball between a lighted lamp and a white screen. From a part of this screen the light will be wholly cut off, and surrounding this area is one from which the light is excluded in part. If three small holes be made in the screen, one where it is darkest, one in the part where it is less dark, and one in the lightest part, it will be found when one looks through them that the flame of the lamp is wholly invisible through the first, a part of it is visible through the second, and the whole flame through the third.

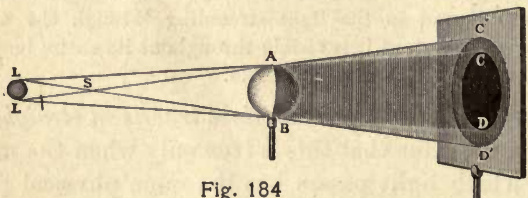


Fig. 184

The space behind the opaque object from which the light is excluded is called the *shadow*. The figure on the screen is a section of the shadow. The darkest part of the shadow, called the *umbra*, is caused by the total exclusion of the light by the opaque object; the lighter part, caused by its partial exclusion, is called the *penumbra*.

When the source of light is a point L (Fig. 183), the shadow will be bounded by a cone of rays, ALB, tangent to the object, and will have only one part, the umbra. When the source of light is an area, such as LL (Fig. 184),

the space $ABDC$ behind the opaque body receives no light, and the parts between AC and AC', and between BD and BD', receives some light, the amount increasing as AC' and BD' are approached. From these figures the cases when the luminous body is larger than the opaque body, and when it is of the same size, may be understood and illustrated by the student.

229. Images by Small Openings. — Support two sheets of cardboard (Fig. 185), in vertical planes. In the center of one cut a hole 2 mm. square, and place in front of it a lighted candle at a distance of 20 or 25 cm. An inverted image of the flame of the candle will appear on the other sheet. If a second small opening be made near the first, a second image will be obtained not coinciding exactly with the first one. The shape of the opening, so long as it is small, has no effect on the image. With a larger opening the image gains in brightness but loses in distinctness.

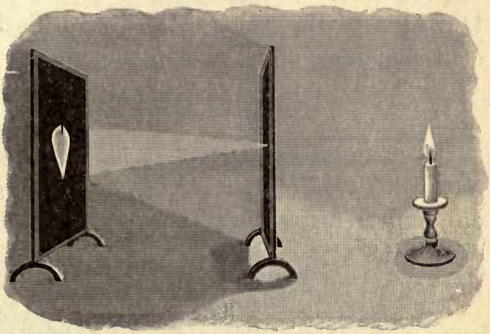


Fig. 185

Every point of the candle flame is the vertex of a cone of rays, or a diverging pencil, passing through the opening and forming an image of it on the screen. These numerous pictures of the opening overlap and form a picture of the flame, and the number at any one place determines the brightness. The edge of the image will therefore be less bright than other portions. In the case of a large opening, the overlapping of the images of the aperture

destroys all resemblance between the image and the object, the resulting image having the shape of the aperture.

230. Illustrations. — The pinhole camera is an application of the foregoing principle. It consists of a small box, blackened within, and provided with a small opening in one face; the light passes through this and forms an image on the sensitized plate placed on the opposite side. When the sun shines through the small chinks in the foliage of a tree, a number of round or oval spots of light may be seen on the ground. These are images of the sun. During a partial solar eclipse such figures assume a crescent shape.

II. PHOTOMETRY

231. Law of Intensity. — The *intensity of illumination is the quantity of light received on a unit of surface.* Everyday experience shows that it varies, not only with the source of the light, but also with the distance at which the source is placed.

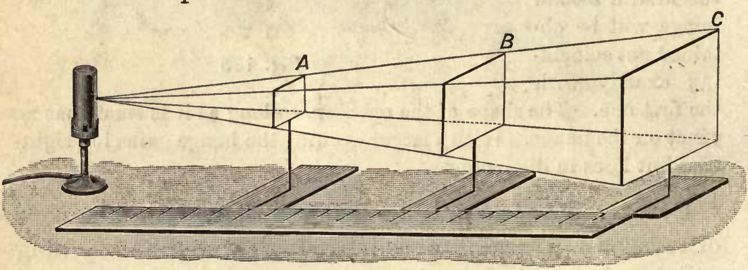


Fig. 186

Cut three cardboard squares, 4, 8, and 12 cm. on a side respectively, and mount them on supports (Fig. 186). The centers of these screens should be at the same distance above the table as the source of light. Use a Welsbach gas lamp with an opaque chimney having a small opening opposite the center of the light, and set it 99 cm. from the

largest screen. Place the medium-sized screen so that it exactly cuts off the light from the edges of the largest. In like manner place the smallest screen with respect to the intermediate one. If these screens are placed with care, it will be found that their distances from the light are 33, 66, and 99 cm. respectively, or as 1 : 2 : 3. Now as each screen exactly cuts off the light from the one next farther away, it follows that each receives the same amount of light from the source when the light is not intercepted. The surfaces of the screens are as 1 : 4 : 9, and hence the quantity of light per unit of surface must be inversely as 1 : 4 : 9, the squares of 1, 2, and 3 respectively.

This experiment shows that *the intensity of illumination varies inversely as the square of the distance from the source of light.* If the medium is such as to absorb some of the light, the decrease in intensity is greater than that expressed by the law of inverse squares.

232. The Bunsen Photometer. — *A photometer is an instrument for comparing the intensity of one light with that*

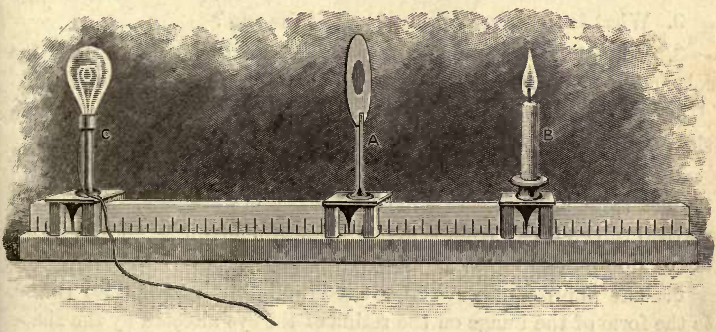


Fig. 187

of another. The principle applied is a consequence of the law of the intensity of illumination; it is that the ratio of the intensities of two lights is equal to the square of the ratio of the distances at which they give equal illumination.

In the Bunsen photometer a screen of paper A (Fig. 187),

having a translucent spot made by applying a little hot paraffin, is supported on a graduated bar between a standard candle B and the light C to be compared with it. An old but imperfect standard candle is the light emitted by the sperm candle of the size known as "sixes," when burning 120 grains per hour. The photometer screen is usually enclosed in a box open toward the two lights, and back of it are two mirrors placed with their reflecting sides toward each other in the form of a V, so that the observer standing by the side of A can see both sides of the screen by reflection in the mirrors. The position of A or of B may then be adjusted until both sides of the screen look alike. Then the intensity of C is to the intensity of B as $\overline{AC}^2$ is to $\overline{AB}^2$.

Questions and Problems

1. What is the cause of an eclipse of the moon?

2. What is the cause of an eclipse of the sun?

3. Why is the duration of a lunar eclipse greater than that of a solar eclipse?

4. Atropine placed in the eye enlarges the pupil. Why is vision then less distinct?

5. An illuminated vertical object 4 feet long is at a distance of 12 feet from a shutter in which there is a minute hole. Inside is a vertical screen 4 feet from the small aperture. How long is the image of the illuminated object given by the small aperture?

6. The pupil of the eye of a cat is elliptical rather than round. Is the form of the image on the retina of the eye affected by the shape of the pupil?

7. If a yardstick standing vertically casts a shadow 2 ft. long, how high is a flagpole that at the same time casts a shadow 100 ft. long?

8. The following data were obtained in measuring the candle power of a Welsbach gas flame: Distance of standard candle from photometer disk, 15 cm.; distance of lamp, 100 cm. What is the candle power of the gas flame?

9. Two lamps of equal candle power are placed 100 m. apart. Where must a screen be placed between them so that one side receives four times as much light as the other?

10. Two electric lights of 16 and 64 candle power, respectively, are placed in front of a picture so as to illuminate it equally. The 16 candle power lamp is 10 ft. from the picture; at what distance is the other one?

III. REFLECTION OF LIGHT

233. Regular Reflection. — When a beam of light falls on a polished plane surface, the greater part of it is reflected in a definite direction. This reflection is known as *regular reflection*. In Fig. 188 a beam of light *IB* is incident on the plane mirror *B* and is reflected as *BR*. *IB* is the *incident beam*, *BR* is the *reflected beam*, the angle *IBP* between the incident beam and the normal (perpendicular) to the reflecting surface is the *angle of incidence*, and the angle *PBR* between the reflected beam and the normal is the *angle of reflection.*

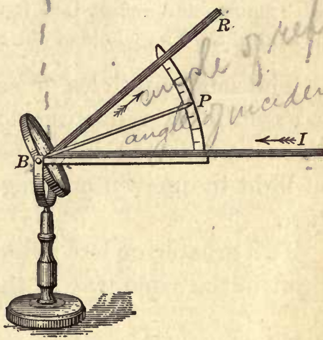


Fig. 188

234. Law of Reflection. — On a semicircular board are mounted two arms, pivoted at the center of the arc (Fig. 189). One arm carries a vertical rod *P*, and the other a paper tube *T* with parallel threads stretched across a diameter at each end. A plane mirror *M*

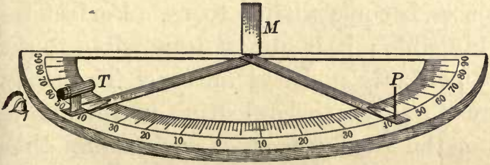


Fig. 189

is mounted at the center of the semicircle, with its reflecting surface parallel to the diameter at the ends of the arc. On the edge of the semicircle is a scale of equal parts with the zero on the normal to the mirror. Place the arm P in any desired position and move the arm T until the image of the rod in the mirror is exactly in line with the two threads. The scale readings will show that the two arms make equal angles with the normal to the mirror. Hence,

The angle of reflection is equal to the angle of incidence, and the two angles lie in the same plane.

235. Diffused Reflection. — Cover a large glass jar with a piece of cardboard, in which is a hole about 1 cm. in diameter. Fill the jar with smoke, and reflect into it through the hole in the cover a beam of sunlight. The whole of the interior of the jar will be illuminated.

The small particles of smoke floating in the jar furnish a great many reflecting surfaces; the light falling on them is reflected in as many directions. The scattering of light by uneven or irregular surfaces is *diffused reflection.*

To a greater or less extent all reflecting surfaces scatter light in the same way as the smoke particles. Figure 190 illustrates in an exaggerated way the difference between a perfectly smooth surface and one somewhat uneven. It is by diffused

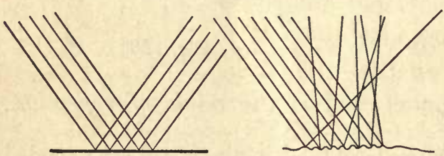


Fig. 190

reflection that objects become visible to us. Perfect reflectors would be invisible; it is almost impossible to see the glass of a very perfectly polished mirror. The trees, the ground, the grass, and particles floating in the air reflect the light from the sun in every direction, and thus fill the space about us with light. If the air were free

from all floating particles and gases, the sky would be dark in all directions, except in the direction of the sun and the stars. This conclusion is confirmed by aëronauts who have reached very high altitudes, where there was almost a complete absence of floating particles.

236. Image of an Object in a Plane Mirror. — Any smooth reflecting surface is called a *mirror*. A *plane mirror* is one whose reflecting surface is a plane. A *spherical mirror* is one whose reflecting surface is a portion of a sphere.

Support a pane of clear window glass in a vertical position, and place a red-colored lighted candle back of it. Place a white candle in front but not lighted. Move the unlighted candle until its image in the glass as a mirror coincides exactly with the lighted candle seen through the glass. The distance of the two candles from the mirror will be the same.

The image of an object in a plane mirror is a *virtual image* because the light only apparently comes from it. *This image is of the same size as the object and is as far back of the mirror as the object is in front.*

237. Geometrical Position of the Image of a Point. — Let A (Fig. 191) be a luminous point in front of a plane mirror MN. Any ray AB incident on the mirror is reflected in the direction BD, making the angle of reflection FBD equal to the angle of incidence FBA. In like manner, a second ray AC is reflected along CE. From A drop a perpendicular AK to the reflecting surface and pro-

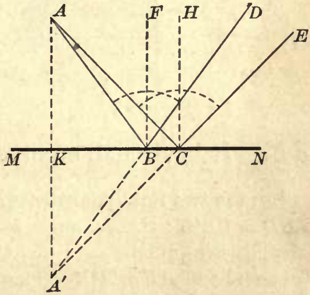


Fig. 191

duce it behind the mirror. Since the incident and reflected rays AB and BD are in the same plane with the normal AK, it follows that BD produced meets the perpendicular in some point A'. The point A' is as far behind the mirror as A is in front.[1] The ray CE produced backwards also meets the perpendicular at A'. But AB and AC are any two rays incident on the mirror. It follows that all rays from A, incident on MN, are reflected from MN as if they came from a point as far back of the mirror as A is in front. Hence the eye placed in the region of D or E will receive the reflected rays as if they came from A'. The point A' is the image of A in the mirror MN, and it is a *virtual image* because the light only *apparently* or *virtually* comes from it. Therefore, *the image of a point in a plane mirror is virtual and is as far back of the mirror as the point is in front of it.*

238. Construction for an Image in a Plane Mirror. — As the image of an object is composed of the images of its points, the image may be located by finding those of its points. Let AB (Fig. 192) represent an object in front of the plane mirror MN. Draw perpendiculars from A and B to the mirror and produce them until their length is doubled. $A'B'$ is the image of AB. It is virtual, erect, and of the same size as the object.

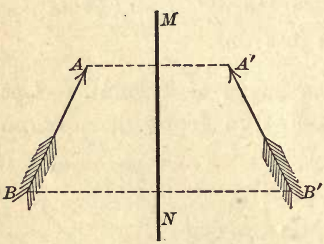


Fig. 192

[1] In the two right triangles ABK and $A'BK$ the angle $KAB = ABF = FBD = BA'K$; that is, angle $KAB =$ angle $BA'K$. Hence the two right triangles are equiangular; and since they have one side in common, they are equal and $AK = A'K$. The same result is reached by the triangles ACK and $A'CK$; the point A' is therefore common to the two rays.

239. Path of the Rays to the Eye. — Let $A'B'$ (Fig. 193) be the image of AB in the plane mirror MN, and E the position of the eye of an observer. To find the path of the rays which enter the eye at E, draw straight lines from A' and B' to E. The intersections C and D of these lines with MN are the points of incidence of the rays from A and B which are reflected to the eye at E. In the same way we may trace the path of the rays for any other position of the eye. Thus we see that while the image does not change, the rays which form it for one observer are not those which form it for another.

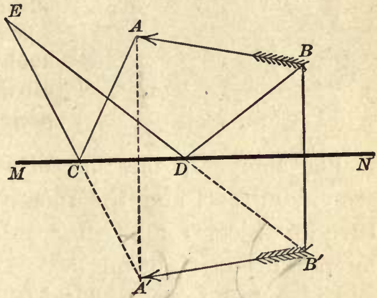


Fig. 193

240. Uses of the Plane Mirror. — The employment of the plane mirror as a "looking glass" dates from a period of great antiquity. The process of covering a glass surface with an amalgam of tin and mercury came into use in Venice about three centuries ago. The process of covering glass with a film of silver was invented during the last century.

The fact that the image in a plane mirror is virtual has been used to produce many optical illusions, such as the stage ghost, the magic cabinet, the decapitated head, etc. To produce the illusion of a ghost, a large sheet of unsilvered plate glass, with its edges hidden by curtains, is so placed that the audience have to look obliquely through it to see the actors on the stage. Other actors, hidden from direct view, and strongly illuminated, are seen by reflection in the glass as ghostly images on the stage.

241. Multiple Reflection. — Place two mirrors so that their reflecting surfaces form an angle (Fig. 194). If a lighted candle be placed between them, several images may be seen in the mirrors; three when they are at right angles, more when the angle is less than a right angle. When the mirrors are parallel, all the images are in a straight line perpendicular to the mirrors.

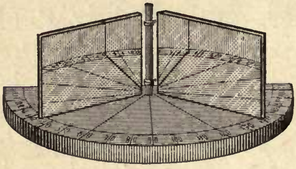


Fig. 194

The image in one mirror serves as an object for the second mirror, and the image in the second becomes in turn an object for the first mirror. In Fig. 195 the two mirrors are at right angles. O' is the image of O in AB, and is found as in § 238. O''' is the image of O' in AC, and is found by the line $O'O'''$ drawn perpendicular to AC produced. O'' is the image of O in AC, and since the mirrors are at right angles, O''' is also the image of O'' in AB. O''' is situated behind the plane of both mirrors, and no images of it can be formed. All the images are situated in the circumference of the circle whose center is A and radius AO. If E is the position of the eye, then O' and O'' are each seen by one reflection, and O''' by two reflections, and for this reason it is less bright.

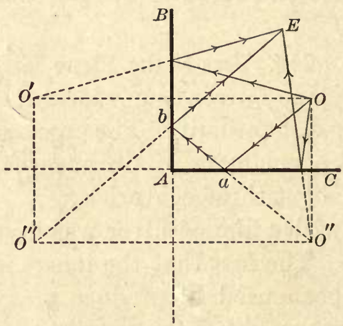


Fig. 195

To trace the path of a ray for the image O''', draw $O'''E$, cutting AB at b, and from the intersection b draw bO'', cutting AC at a. Join aO; the path of the ray is $OabE$.

It is interesting to find the images when the mirrors are at various angles.

242. Applications. — The double image of a bright star and the several images of a gas jet in a thick mirror (Fig. 196) are examples of multiple reflection, the front surface of the mirror and the metallic surface at the back serving as parallel reflectors. Geometrically the number of images is infinite; but on account of their faintness only a limited number is visible. The *kaleidoscope*, a toy invented by Sir David Brewster, is an interesting application of the same principle. It consists of a tube containing three mirrors extending its entire length, the angle between any two of them being 60°. One end of the tube is closed by ground glass, and the other by a cap with a round hole in it. Pieces of colored glass are placed loosely between the ground glass and a plate of clear glass parallel to it. On looking through the whole at any source of light, multiple images of these pieces of glass are seen, symmetrically arranged around the center, and forming beautiful figures, which vary in pattern with every change in the position of the pieces of glass.

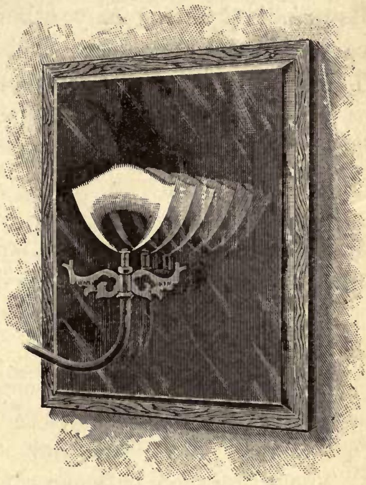


Fig. 196

243. Spherical Mirrors. — A mirror is *spherical* when its reflecting surface is a portion of the surface of a sphere. If the inner surface is polished for reflection, the mirror is *concave;* if the outer surface, it is *convex.* Only a small portion of a spherical surface is used as a mirror. In Fig. 197 the *center C* of the mirror *MN* is the center of curvature of the sphere of which the reflecting surface is a part. The middle

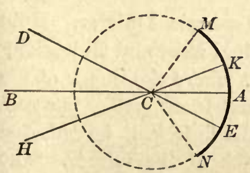


Fig. 197

point A of the reflecting surface MN is the *pole* or *vertex* of the mirror, and the straight line AB passing through the center of curvature C and the pole A of the mirror is its *principal axis*. Any other straight line through the center and intersecting the mirror is a *secondary axis*. The figures of spherical mirrors in this chapter are sections of a sphere made by passing a plane through the principal axis.

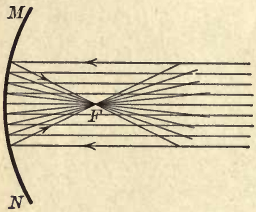


Fig. 198

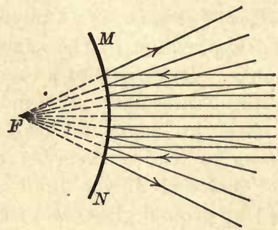


Fig. 199

The difference between a plane mirror and a spherical one is that the normals to a plane mirror are all parallel lines, while those of a spherical mirror are the radii of the surface, and all pass through the center of curvature.

244. Principal Focus of Spherical Mirrors. — *A focus* is the point common to the paths of all the reflected rays of a pencil of light. It is a *real* focus if the rays of light actually pass through the point, Fig. 198, and *virtual* if they only appear to do so (Fig. 199).

Let the rays of the sun fall on a concave spherical mirror. Hold a graduated ruler in the position of its principal axis, and slide along it a small strip of cardboard. Find the point where the image of the sun is smallest. This will mark the principal focus, and it is a real one. If a convex spherical mirror be used, the light will be reflected as a broad pencil diverging from a point back of the mirror. The focus is then a virtual one.

If a pencil of parallel rays falls on a concave spherical mirror, parallel to its principal axis, the point to which the rays converge after reflection is called the *principal focus* of the mirror. In the case of a convex spherical mirror, the principal focus is the point on the axis behind the mirror from which the reflected rays diverge. The distance of the principal focus from the mirror is its *principal focal length.*

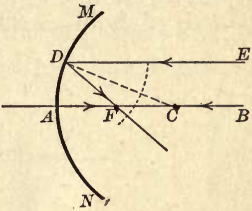


Fig. 200

245. The Position of the Principal Focus. — Let *MN* (Fig. 200) be a concave mirror whose center is at *C* and principal axis is *AB*. Let *ED* be a ray parallel to *BA*. Then *CD* is the normal at *D*; and *CDF*, the angle of reflection, must equal *EDC*, the angle of incidence. Since the ray *BA* is normal to the mirror, it will be reflected back along *AB*. The reflected rays *DF* and *AB* have a common point *F*, which is the principal focus. The triangle *CFD* is isosceles with the sides *CF* and *FD* equal. (Why?) But when the point *D* is near *A*, *FD* is equal to *FA*; *F* is therefore the middle point of the radius *CA*. Other rays parallel to *BA* will pass after reflection nearly through *F*. Hence, *the principal focus of a concave spherical mirror is real and is halfway between the center of curvature and the vertex.*

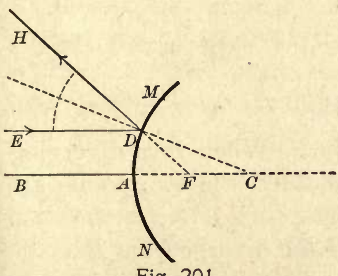


Fig. 201

Let *MN* (Fig. 201) be a convex spherical mirror. *ED* and *BA* are rays parallel to the principal axis. When produced back of the mirror,

after reflection, their common point F is back of the mirror and halfway between A and C. (Why?) Hence, *the principal focus of a convex spherical mirror is virtual and halfway between the center of curvature and the mirror.*

246. Conjugate Foci of Mirrors. — When a diverging pencil of light ABD (Fig. 202) falls on the spherical

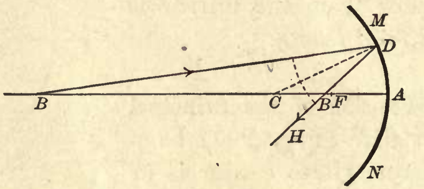


Fig. 202

mirror MN, it is focused after reflection at a point F on the axis AB which passes through the radiant point or source of light; after reflection the rays diverge from this

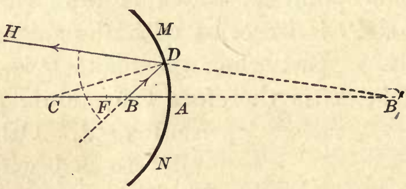


Fig. 203

focus F as a new radiant point. When rays diverging from one point converge to another, the two points are called *conjugate foci.*

In Fig. 203, the rays BA and BD diverge from B as the radiant point; after reflection they diverge as if they came from B' behind the reflecting surface; B' is a virtual focus and B and B' are conjugate foci.

In the first case the source of light is farther from the mirror than the center of curvature, and the focus is real; in the second case it is nearer the mirror than the principal focus, and the focus is virtual.[1]

247. Images in Spherical Mirrors. — In a darkened room support on the table a concave spherical mirror, a lamp, and a small white screen. Place the lamp anywhere beyond the focus, and move the screen until a clear image of the flame is formed on it (Fig. 204). Notice the size and position of the image, and whether it is erect or inverted. When the lamp is between the focus and the mirror, an image of it cannot be obtained on the screen, but it can be seen by looking into the mirror. The same is true for the convex mirror, whatever be the position of the lamp; in these last cases the image is a virtual one.

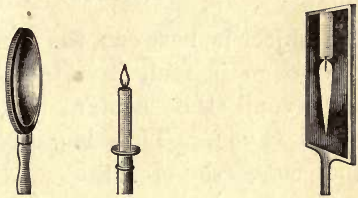


Fig. 204

The experiment shows the relative positions of the object and its image for a concave mirror, all depending on the position of the object with respect to the mirror. If these positions are carefully noted it will be seen that there are six distinct cases as follows:

[1] In Fig. 202, CD bisects the angle BDH. Hence, $\frac{BD}{B'D} = \frac{BC}{B'C}$. If D is close to A, we may, without sensible error, place $BD = BA$ and $B'D = B'A$. Put $BA = p$, $B'A = q$, $CA = r = 2f$. Then $BC = p - r$, $B'C = r - q$, and $\frac{p}{q} = \frac{p-r}{r-q}$, from which $\frac{1}{p} + \frac{1}{q} = \frac{2}{r} = \frac{1}{f}$. By measuring p and q, we may compute r and f. For the convex mirror, q and r are negative.

First. — When the object (AB, Fig. 205) is at a finite distance beyond the center of curvature, the image is real, inverted, smaller than the object, and between the center of curvature and the principal focus.

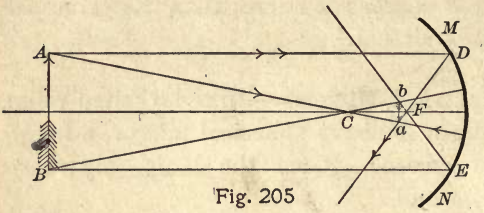


Fig. 205

Second.—When the object is between the center and the principal focus, the image is real, inverted, larger than the object, and is beyond the center (Fig. 206). This is the converse of case one.

Third. — When a small object is at the center of curvature, the image is real, inverted, of the same size as the object, and at the center of curvature (Fig. 207).

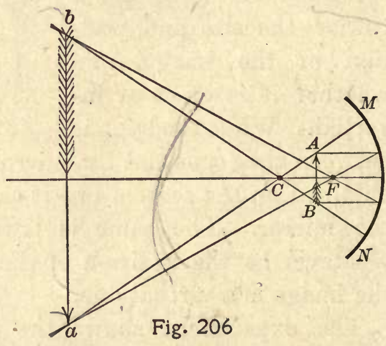


Fig. 206

Fourth. — When the object is at the principal focus, the rays are reflected parallel to the principal axis, and no image is formed (Fig. 208).

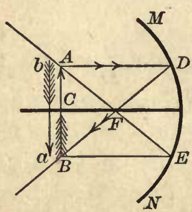


Fig. 207

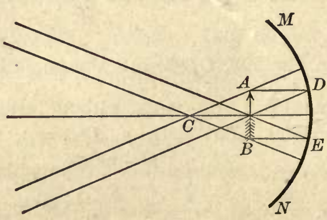


Fig. 208

Fifth. — When the object is between the principal focus and the mirror, the image is virtual, erect, and larger than the object (Fig. 209).

Sixth. — When the mirror is convex, the image is always virtual, erect, and smaller than the object (Fig. 210).

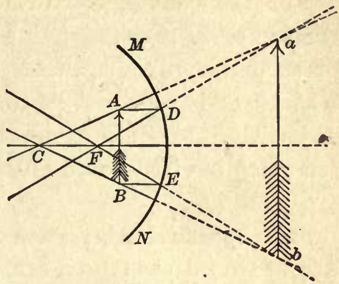


Fig. 209

248. Construction for Images. — To find images in spherical mirrors by geometrical construction, it is only necessary to find conjugate focal points. To do this trace two rays for each point for the object, one along the secondary axis through it, and the other parallel to the principal axis. The first ray is reflected back on itself, and the second through the principal focus. The intersection of the two reflected rays from the same point of the object locates the image of that point.

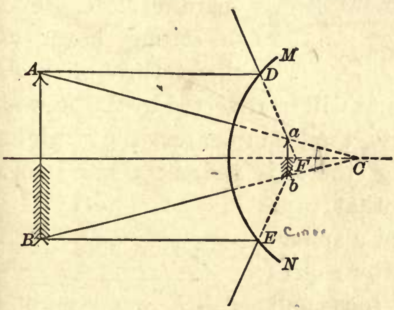


Fig. 210

For instance: In Fig. 205, AC is the path of both the incident and the reflected ray, while the ray AD is reflected through the principal focus F. Their intersection is at a. The rays BC and BE are reflected similarly through b. Hence, ab is the image of AB. In Fig. 209, the ray AC along the secondary axis, and AD reflected back through F as DF, must be produced to meet back of

the mirror at the virtual focus *a*. *A* and *a* are conjugate foci; also *B* and *b*, and *ab* is a virtual image.

For the convex mirror (Fig. 210) the construction is the same. From the point *A* draw *AC* along the normal or secondary axis, and *AD* parallel to the principal axis. The latter is reflected so that its direction passes through *F*. The intersection of these two lines is at *a*. The image *ab* is virtual and erect.

249. Spherical Aberration in Mirrors. — Bend a strip of bright tin into as true a semicircle as possible and fasten it to a vertical board as in Fig. 211. At right angles to the board at one end place a vertical sheet of cardboard containing three parallel slots. Send a strong beam of light through each of these slots; the three beams will be reflected by the curved tin through different points, the beam nearest the straight rim of the mirror crossing the axis nearest the mirror.

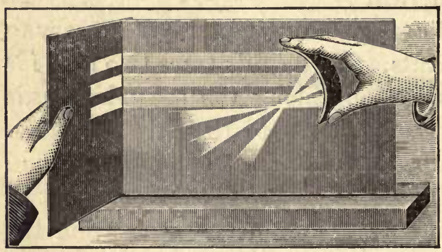


Fig. 211

The experiment shows that rays incident near the margin of a spherical mirror cross the axis after reflection between the principal focus and the mirror. This spreading out of the focus is known as *spherical aberration by reflection*. It causes a lack of sharpness in the outline of images formed by spherical mirrors. It is

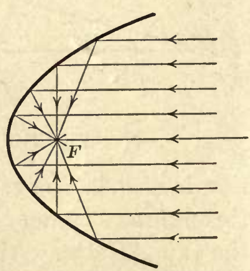


Fig. 212

reduced by decreasing the aperture of the mirror by means of a diaphragm to cut off marginal rays, or by decreasing the curvature of the mirror from the vertex outward. The result then is a parabolic mirror (Fig. 212), which finds use in searchlights, lighthouses, headlights of locomotives, and in reflecting telescopes.

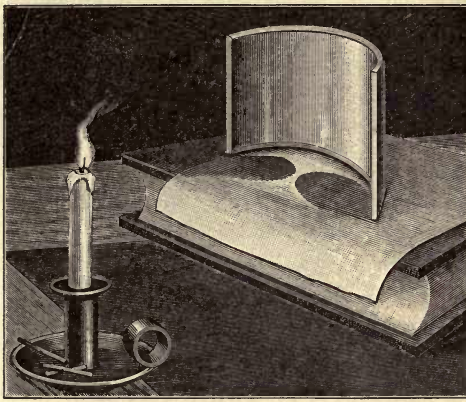


Fig. 213

250. Caustics by Reflection. — Use the tin reflector of the last experiment as shown in Fig. 213. The light from a candle or a lamp is focused on a curved line.

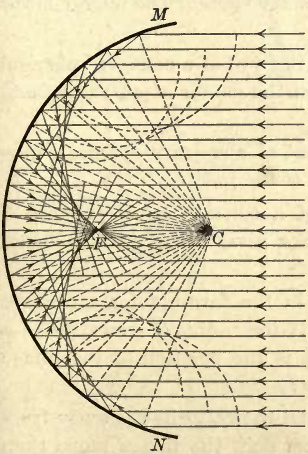


Fig. 214

The curve formed by the rays reflected from a spherical mirror is called the *caustic by reflection.* It may be seen by letting sunlight fall on a tin milk pail partly full of milk, or on a plain gold ring on a white surface. The caustic curve may be constructed by drawing a series of parallel rays incident on a concave mirror of large aperture (Fig. 214), and tracing the reflected

rays by means of the law of reflection, that is, making in each case the angle of reflection equal to the angle of incidence. The caustic is the curved line to which all of the reflected rays are tangent. It should be noticed that in the case of a concave spherical mirror the caustic is a surface.

Problems

1. Two mirrors are placed at an angle of 45°. Find graphically how many images there are of a point situated between the mirrors.

2. Show by a diagram that a person can see his whole length in a mirror of half his height.

3. Which will give the stronger illumination of your book, a 16 candle power light at a distance of 2 ft., or a 32 candle power light at a distance of 4 ft.?

4. An object placed 8 ft. in front of a concave spherical mirror gave an image 2 ft. from the mirror. What was the principal focal length of the mirror?

5. An object is placed 20 cm. in front of a concave mirror having a principal focal length of 30 cm. How far back of the mirror is the image?

6. Where must an object be placed in front of a concave spherical mirror to get an image halfway between the center of curvature and the principal focus?

7. An object is placed 20 in. in front of a concave spherical mirror of 10 in. radius. Find the position of the image.

8. Find the radius of curvature of a concave spherical mirror when an object 100 cm. from the mirror gives a real image 50 cm. from the mirror.

9. By making f, r, and q negative in the formula for a concave mirror, it applies to a convex mirror. If the radius of curvature of a convex spherical mirror is 20 in., what is the position of the image when the object is 5 ft. from the mirror?

10. If a plane mirror is moved parallel to itself directly away from an object in front of it, how much faster does the image move than the mirror?

IV. REFRACTION OF LIGHT

251. Refraction. — Fasten a paper protractor scale centrally on one face of a retangular battery jar (Fig. 215), and fill the jar with water to the horizontal diameter of the scale. Place a slotted cardboard over the top. With a plane mirror reflect a beam of light through the slit into the jar, at such an angle that the beam is incident on the water exactly back of the center of the scale. The path of this ribbon of light may be traced; its direction is changed at the surface of the water.

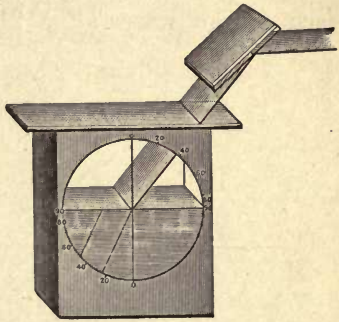


Fig. 215

The change in the course of light in passing from one transparent medium into another is called *refraction*.

Place a coin at the bottom of an empty cup standing on a table, and let an observer move back until the coin just passes out of sight below the edge of the cup; now pour water into the cup, and the coin will come into view (Fig. 216).

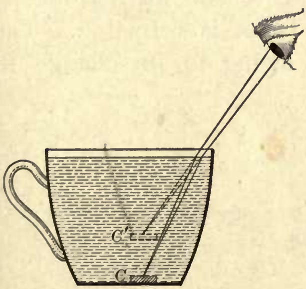


Fig. 216

The changes in the apparent depth of a pond or a stream, as the observer moves away from it, are caused by refraction. The broken appearance of a straight pole thrust obliquely into water is accounted for by the change in direction which the rays coming from the part under water suffer as they emerge into the air.

252. Cause of Refraction. — Foucault in France and Michelson in America have measured the velocity of light in water, and have found that it is only three fourths as

$\frac{3}{4}$

great as in air. The velocity of light in all transparent liquids and solids is less than in air, while the velocity in air is practically the same as in a vacuum.

If now a beam of light is incident obliquely on the surface *MN* of water (Fig. 217), all parts of a wave do not enter the water at the same time. Let the parallel lines perpendicular to *AB* represent short portions of plane waves. Then one part of a wave, as *f*, will reach the water before the other part, as *e*, and will travel less rapidly in the water than in the air. The result is that each wave is swung around, that is, the direction of propagation *BC*, which is perpendicular to the wave fronts, is changed; in other words, the beam is refracted. The refraction of light is therefore owing to its change in velocity in passing from one transparent medium to another.

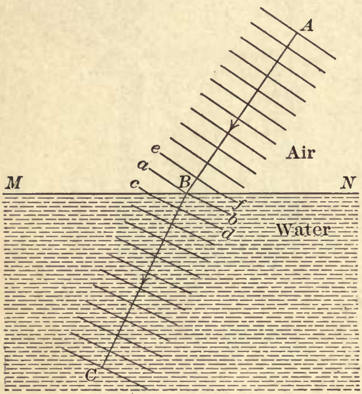


Fig. 217

253. The Index of Refraction. — Let a beam of light pass obliquely from air to water or glass, and let *AB* (Fig. 218) be the incident wave front. From *A* as a center and with a radius *AD* equal to the distance the light travels in the second medium while it is going from *B* to *C* in air, draw

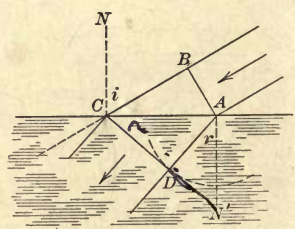


Fig. 218

the dotted arc. This limits the distance to which the disturbance spreads in the second medium. Then from C draw CD tangent to this arc and draw AD to the point of tangency. CD is the new wave front.

The distances BC and AD are traversed by the light in the same time. They are therefore proportional to the velocities of light in the two media. Then

the index of refraction n

$$= \frac{\textit{the velocity of light in air}}{\textit{the velocity of light in the second medium}} = \frac{v}{v'}.^{1}$$

The angle NCB is the *angle of incidence*. It is equal to the angle BAC between the incident wave front and the surface of separation of the two media. The *angle of refraction* is the angle $N'AD$. It is equal to the angle ACD between the wave front in the second medium and the surface of separation. The angle at C, between the direction of the incident ray and the refracted ray, is the *angle of deviation.*

The following are the indices of refraction for a few substances:

Water	. . . 1.33	Crown glass	. . . 1.51
Alcohol	. . . 1.36	Flint glass	. 1.54 to 1.71
Carbon bisulphide	1.64	Diamond	. . . . 2.47

[1] The older mathematical definition of the index of refraction is the ratio of the sine of the angle of incidence to the sine of the angle of refraction. Now the sine of an angle in a right triangle is the quotient of the side opposite by the hypotenuse. Thus, the sine of angle BAC is $\frac{BC}{AC}$, and the sine of ACD is $\frac{AD}{AC}$. Dividing one by the other, the common term AC cancels out, and the index of refraction equals $\frac{BC}{AD} = \frac{v}{v'}$, as before. The two definitions are therefore equivalent to each other. For the construction to find the refracted ray, see the Appendix.

254. Laws of Refraction. — The following laws, which summarize the facts relative to single refraction, were discovered by Snell, a Dutch physicist, in 1621:

I. *When a pencil of light passes obliquely from a less highly to a more highly refractive medium, it is bent toward the normal; when it passes in the reverse direction, it is bent from the normal.*

II. *Whatever the angle of incidence, the index of refraction is a constant for the same two media.*

III. *The planes of the angles of incidence and refraction coincide.*

255. Refraction through Plate Glass. — Draw a heavy black line on a sheet of paper, and place over it a thick plate of glass, covering a part of the line. Look obliquely through the glass; the line will appear broken at the edge of the plate, the part under the glass appearing laterally displaced (Fig. 219).

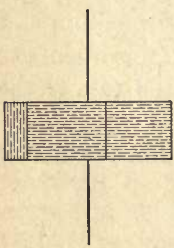


Fig. 219

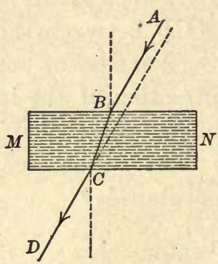


Fig. 220

To explain this, let *MN* (Fig. 220) represent a thick plate of glass, and *AB* a ray of light incident obliquely upon it. If the path of the ray be determined, the emergent ray will be parallel to the incident ray. Hence, the apparent position of an object viewed through a plate is at one side of its true position.

256. A Prism. — Let *ABC* (Fig. 221) represent a section of a glass prism made by a plane perpendicular to the re-

fracting edge A. Also, let LI be a ray incident on the face BA. This ray will be refracted along IE, and entering the air at the point E will be refracted again, taking the direction EO.

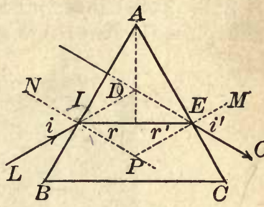


Fig. 221

Reflect across the table a strong beam of light and intercept it with a sheet of green glass. Let this ribbon of green light be incident on a prism of small refracting angle in such a manner that only part of the beam passes through the prism. Two lines of light may be traced through the dust of the room or by means of smoke. By turning the prism about its axis, the angle between these lines of light can be varied in size. It is the angle of deviation, represented by the angle D in the figure. The angle of deviation is least when the angles of incidence and emergence are equal; this occurs when the path of the ray through the prism is equally inclined to the two faces.

257. Atmospheric Refraction. — Light coming to the eye from any heavenly body, as a star, unless it is directly overhead, is gradually bent as it passes through the air on account of the increasing density of the atmosphere near the earth's surface. Thus, if S in Fig. 222 is the real position of a star, its apparent position will be S' to an observer at E.

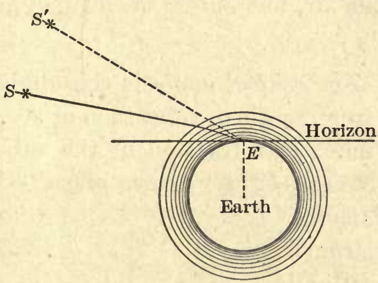


Fig. 222

Such an object appears higher above the horizon than its real altitude. The sun rises earlier on account of atmospheric refraction than it otherwise would, and for the same reason it sets later. Twilight, the mirage of the

desert, and the looming of distant objects are phenomena of atmospheric refraction.

258. Total Internal Reflection. — Take the apparatus of § 251 and place the cardboard against the end of the jar so that the slit is near the bottom (Fig. 223). Reflect a strong beam of light up through the water and incident on its under surface just back of the protractor scale. Adjust the slit so that the beam shall be incident at an angle a little greater than 50°. It will be reflected back into the water as from a plane mirror.

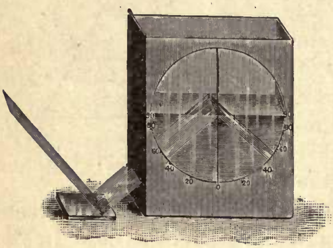


Fig. 223

As the angle of refraction is always greater than the angle of incidence when the light passes from water into air, it is evident that there is an incident angle of such a value that the corresponding angle of refraction is 90°, that is, the refracted light is parallel to the surface. If the angle of incidence is still further increased, the light no longer passes out into the air, but suffers *total internal reflection*.

259. The Critical Angle. — *The critical angle* is the angle of incidence corresponding to an angle of refraction of 90°. This angle varies with the index of refraction of the substance. It is about 49° for water, 42° for crown glass, 38° for flint glass, and 24° for diamond.

Of all the rays diverging from a point at the bottom of a pond and incident on the surface, only those within a cone whose semi-angle is 49° pass into the air. All those incident at a larger angle undergo total internal reflection (Fig. 224).

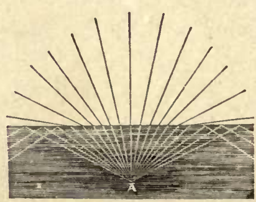


Fig. 224

Hence, an observer under water sees all objects outside as if they were crowded into this cone; beyond this he sees by reflection objects on the bottom of the pond.

Total reflection in glass is shown by means of a prism whose cross section is a right-angled isosceles triangle (Fig. 225). A ray incident normally on either face about the right angle enters the prism without refraction, and is incident on the hypotenuse at an angle of 45°, which is greater than the critical angle. The ray therefore suffers total internal reflection and leaves the prism at right angles to the incident ray. A similar prism is sometimes used in a projecting lantern for making the image erect (Fig. 226). It would otherwise be inverted with respect to the object.

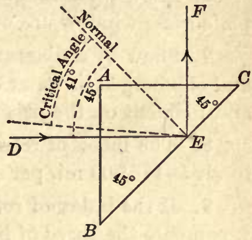


Fig. 225

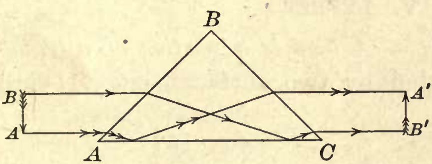


Fig. 226

Problems

1. Where would you place a lamp in front of a concave spherical mirror to get an image of the lamp on the wall larger than the lamp itself? Illustrate by a figure.

2. Why does the full moon as it rises appear to be oblong with the major axis horizontal?

3. What deviation is produced by reflection from a plane mirror when the angle of incidence is 60°?

4. Paste diamonds are made of flint glass and have about the same index of refraction as carbon bisulphide. A diamond is visible in carbon bisulphide and the paste diamond is not. Explain.

5. A bottle filled with pounded glass is opaque, and is translucent when spirits of turpentine are added. Explain.

6. Show by a diagram that objects viewed obliquely through a plate glass window are not seen exactly in their true position.

7. Show by a diagram the effect of a hollow prism filled with air and submerged in water on a beam of light passing through the water and incident on the prism.

8. The index of refraction for water is $\frac{4}{3}$. If the velocity of light in air is 186,000 mi. per second, what is it in water?

9. If the index of refraction for crown glass is $\frac{3}{2}$, and for water is $\frac{4}{3}$, compare the speed of light in crown glass with that in water. What simple fraction represents the relative speed?

10. Will a pencil of light passing obliquely from water into flint glass be bent toward or away from the perpendicular in the glass?

V. LENSES

260. Kinds of Lenses. — *A lens is a portion of a transparent substance* bounded by two surfaces, one or both

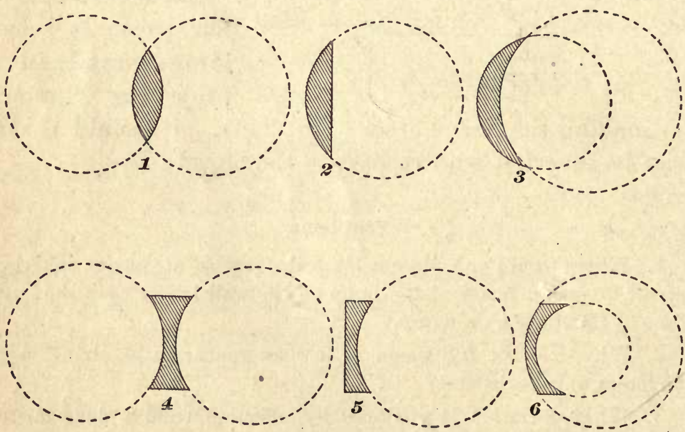


Fig. 227

being curved. The curved surfaces are usually spherical (Fig. 227). Lenses are classified as follows:

1. Double-convex, — both surfaces convex . .
2. Plano-convex, — one surface convex, one plane . . . .
3. Concavo-convex, — one surface convex, one concave . . . .

} **Converging lenses, thicker at the middle than at the edges.**

4. Double-concave, — both surfaces concave .
5. Plano-concave, — one surface concave, one plane . . . .
6. Convexo-concave, — one surface concave, one convex . . . .

} **Diverging lenses, thinner at the middle than at the edges.**

The concavo-convex and the convexo-concave lenses are frequently called *meniscus* lenses. The double-convex lens may be regarded as the type of the converging class of lenses, and the double-concave lens of the diverging class.

261. Definition of Terms relating to Lenses. — The centers of the spherical surfaces bounding a lens are the *centers of curvature*. The *optical center* is a point such that any ray passing through it and the lens suffers no change of direction. In lenses whose surfaces are of equal curvature, the optical center is their center of volume, as O, in Fig. 228. In plano-

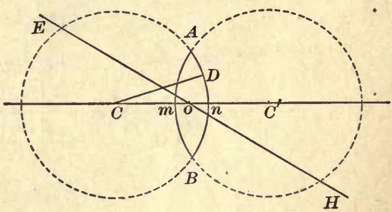


Fig. 228

lenses, the optical center is the middle point of the curved face. The straight line, CC', through the centers of curvature, is the *principal axis*, and any other straight line through the optical center as EH, is a *secondary axis*. The normal at any point of the surface is the radius of the sphere drawn to that point; thus CD is the normal to the surface AnB at D.

262. Tracing Rays through Lenses. — A study of Figs. 229 and 230 shows that the action of lenses on rays of light traversing them is similar to that of prisms, and conforms to the principle illustrated in § 256. A ray is always refracted *toward* the perpendicular on entering a

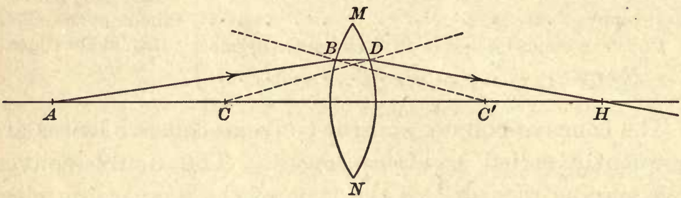


Fig. 229

denser medium (glass), and *away from* it on entering a medium of less optical density. Thus we see that the convex lens bends a ray toward the principal axis, while the concave lens (Fig. 230) bends it away from this axis.

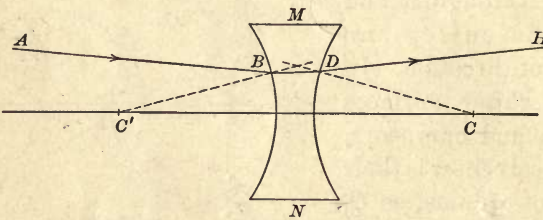


Fig. 230

263. The Principal Focus. — Hold a converging lens so that the rays of the sun fall on it parallel to its principal axis. Beyond the lens hold a sheet of white paper, moving it until the round spot of light is smallest and brightest. If held steadily, a hole may be burned through the paper. This spot marks the *principal focus* of the lens, and its distance from the optical center is the *principal focal length.*

Converging lenses are sometimes called *burning glasses* because of their power to focus the heat rays, as shown in the experiment.

Figure 231 shows that parallel rays are made to converge toward the principal focus *F* by a converging lens, and

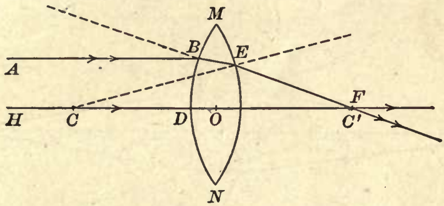


Fig. 231

the focus is *real*; on the other hand, Fig. 232 illustrates the diverging effect of a concave lens on parallel rays; the focus *F* is now virtual because the rays after passing

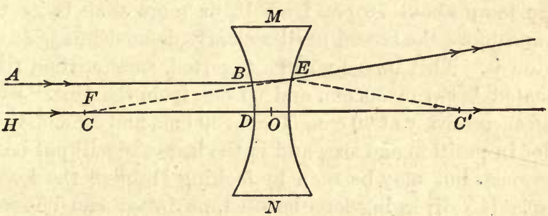


Fig. 232

through the lens only apparently come from *F*. In general, converging lenses increase the convergence of light, while diverging lenses decrease it.

264. Conjugate Foci of Lenses. — If a pencil of light diverges from a point and is incident on the lens, it is focused at a point on the axis through the radiant point.

These points are called *conjugate foci*, for the same reason as in mirrors.

In Fig. 233 a pencil of rays BAE diverges from A and is focused by the lens at the point H. It is evident that if the rays diverge from H, they would be brought to a focus at A. Hence A and H are *conjugate foci.*

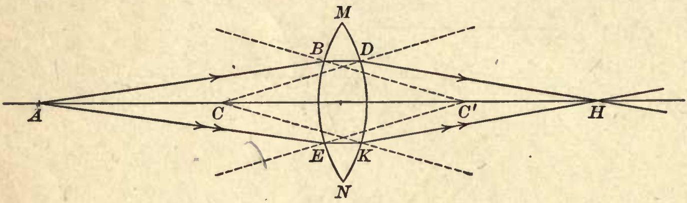


Fig. 233

265. Images by Lenses. — Place in line on the table in a darkened room a lamp, a converging lens of known focal length, and a white screen. If, for example, the focal length of the lens is 30 cm., place the lamp about 70 cm. from it, or more than twice the focal length, and move the screen until a clearly defined image of the lamp appears on it. This image will be inverted, smaller than the object, and situated between 30 cm. and 60 cm. from the lens. By placing the lamp successively at 60 cm., 50 cm., 30 cm., and 20 cm., the images will differ in position and size, and in the last case will not be received on the screen, but may be seen by looking through the lens toward the lamp. If a diverging lens be used, no image can be received on the screen because they are all virtual.

The results of such an experiment may be summarized as follows:

I. When the object is at a finite distance from a converging lens, and farther than twice the focal length, the image is real, inverted, at a distance from the lens of more than once and less than twice the focal length, and smaller than the object (Fig. 234).

II. When the object is at a distance of twice the focal length from a converging lens, the image is real, inverted,

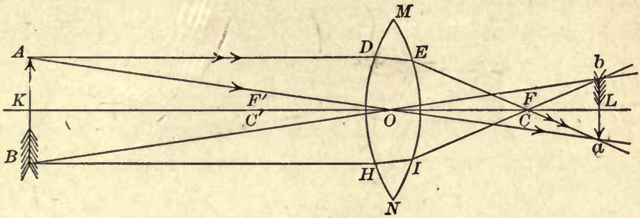


Fig. 234

at the same distance from the lens as the object, and of the same size (Fig. 235).

III. When the object is at a distance from a converging lens of less than twice and more than once its

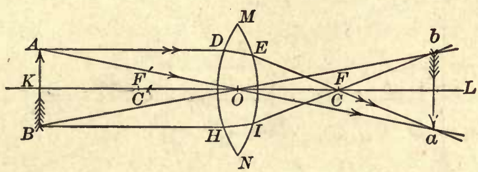


Fig. 235

focal length, the image is real, inverted, at a distance of more than twice the focal length, and larger than the object (Fig. 236).

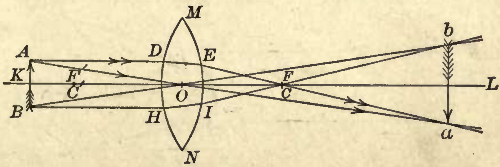


Fig. 236

IV. When the object is at the principal focus of a converging lens, no distinct image is formed (Fig. 237).

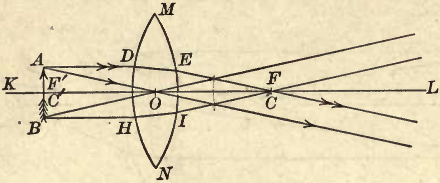


Fig. 237

V. When the object is between a converging lens and its principal focus, the image is virtual, erect, and enlarged (Fig. 238).

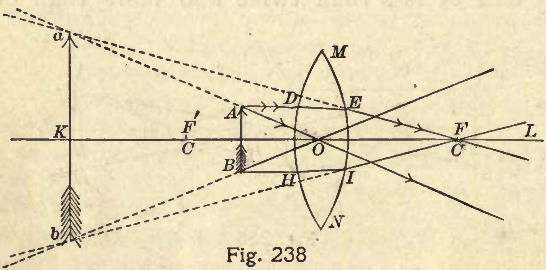


Fig. 238

VI. With a diverging lens, the image is always virtual, erect, and smaller than the object (Fig. 239).

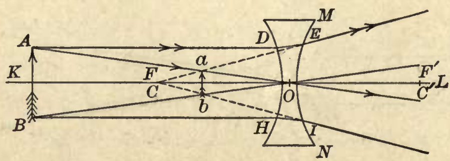


Fig. 239

266. Graphic Construction of Images by Lenses. — The image of an object by a lens consists of the images of its points. If the object is represented by an arrow, it is necessary to find only the images of its extremities. This is readily done by following two general directions:

First. Draw secondary axes through the ends of the arrow. These represent rays that suffer no change in direction because they pass through the optical center (§ 261).

Second. Through the ends of the arrow draw rays parallel to the principal axis. After leaving the lens, these pass through the principal focus (§ 263).

The intersection of the two refracted rays from each extremity will be its image.

To illustrate. Let AB be the object and MN the lens (Figs. 234–239). Rays along secondary axes through O pass through the lens without any change in direction. The rays AD and BH, parallel to the principal axis, are refracted in the lens along DE and HI respectively, and emerge from the lens in a direction which passes through the principal focus F. The intersection of Aa with Ea is the image of A, and that of Bb with Ib is the image of B. Other rays from A and B also pass through a and b respectively, and therefore ab is the image of AB. The image is virtual when the intersection of the refracted rays is on the same side of the lens as the object. The relative size of object and image is the same as their relative distance from the lens.

267. Spherical Aberration in Lenses. — If rays from any point be drawn to different parts of a lens, and their directions be determined after refraction, it will be found that those incident near the edge of the lens cross the

principal axis, after emerging, nearer the lens than those incident near the middle. The principal focal length for the marginal rays is therefore less than for central rays. This indefiniteness of focus is called *spherical aberration by refraction*, the effect of which is to lessen the distinctness of images formed by the lens. In practice a round screen, called a *diaphragm*, is used to cut off the marginal rays; this renders the image sharper in outline, but less bright. In the large lenses used in telescopes the curvature of the lens is made less toward the edge, so that all parallel rays are brought to the same focus.

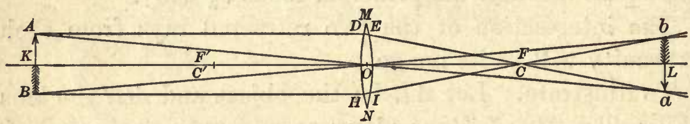


Fig. 240

268. Formula for Lenses. — The triangles AOK and aOL in Fig. 240 are similar. Hence, $\frac{AK}{aL}=\frac{KO}{LO}$. If the lens is *thin*, a straight line connecting D and H will pass very nearly through the optical center O. Then DFO is a triangle similar to aFL, and $\frac{DO}{aL}=\frac{OF}{LF}$. Since DO is equal to AK, the first members of the two equations above are equal to each other, and therefore $\frac{KO}{LO}=\frac{OF}{LF}$. Put $KO=p$, $LO=q$, and $OF=f$. Then $LF=q-f$, and

$$\frac{p}{q}=\frac{f}{q-f}.$$

Clearing of fractions and dividing through by pqf, we have

$$\frac{1}{f}=\frac{1}{p}+\frac{1}{q}. \quad . \quad . \quad . \quad . \quad . \quad . \qquad \text{(Equation 32)}$$

By measuring p and q we may compute f. For diverging lenses f and q are negative.

Questions and Problems

1. Given a spectacle lens, how will you determine whether it is converging or diverging?

2. Where must the observer place himself so as to see his own image in a concave mirror?

3. Why is the image of yourself in the bowl of a silver spoon distorted?

4. What kind of mirrors and lenses always produce virtual images?

5. If one half of a converging lens is covered by an opaque card, what will be the effect on the real image?

6. When an object moves from a great distance up to twice the focal length of a converging lens, how far does the image move?

7. A candle is placed 10 ft. from a white wall. Find the position of a converging lens that will give an enlarged image of the candle on the wall, the focal length of the lens being 20 in.

8. Why does a mirror made of plate glass give a better image than one made of common window glass?

9. What is the smallest distance between an object and its real image in a converging lens, expressed in terms of the focal length?

10. The focal length of a camera lens is 20 cm. How far from the lens must the sensitized plate be placed when the object is 200 cm. from the lens?

11. An object 5 cm. long in front of a converging lens has an image 20 cm. long on a screen 100 cm. from the lens. What is the focal length of the lens?

12. An object is placed 100 cm. from a diverging lens whose focal length is $33\frac{1}{3}$ cm. What is the distance of the virtual image?

VI. OPTICAL INSTRUMENTS

269. The Magnifying Glass, or *simple microscope*, is a double-convex lens, usually of short focal length. The object must be placed nearer the lens than its principal focus. The image is then virtual, erect, and enlarged.

If AB is the object in Fig. 241, the virtual image is ab; and if the eye be placed near the lens on the side opposite

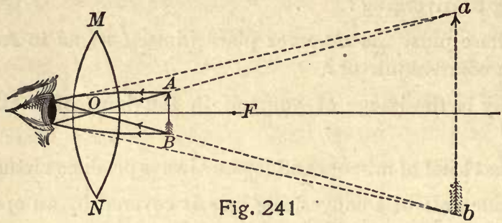


Fig. 241

the object the virtual image will be seen in the position of the intersection of the rays produced, as at ab.

270. The Compound Microscope (Fig. 242) is an instrument designed to obtain a greatly enlarged image of very small objects. In its simplest form it consists of a converging lens MN (Fig. 243), called the *object glass* or *objective*, and another converging lens RS, called the *eyepiece*. The two lenses are mounted in the ends of the tube of Fig. 242. The object is placed on the stage just under the objective, and a little beyond its principal focus. A real image ab (Fig. 243) is formed slightly nearer the eyepiece than its focal length. This image formed by the objective is viewed by the eyepiece, and the latter gives an enlarged virtual image.

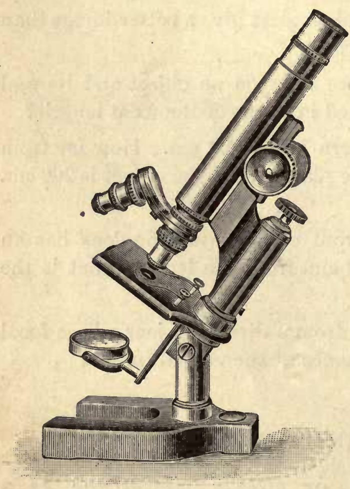


Fig. 242

(Why?) Both the objective and the eyepiece produce magnification.

271. The Astronomical Telescope. — The system of lenses in the refracting astronomical telescope (Fig. 244) is similar to that of the compound microscope. Since it is intended to view distant objects, the objective *MN* is of

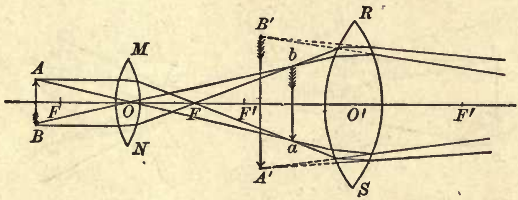


Fig. 243

large aperture and long focal length. The real image given by it is the object for the eyepiece, which again forms a virtual image for the eye of the observer. The magnification is the ratio of the focal lengths of the objective and the eyepiece. The objective must be large, for

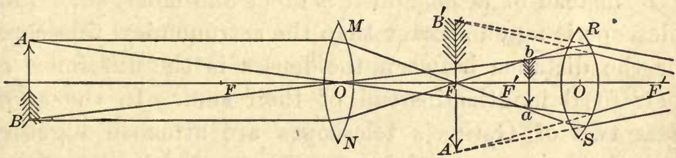


Fig. 244

the purpose of collecting enough light to permit large magnification of the image without too great loss in brightness.

Figure 244 shows that the image in the astronomical telescope is inverted. In a terrestrial telescope the image is made erect by introducing near the eyepiece two double-

convex lenses, in such relation to each other and to the first image that a second real image is formed like the first, but erect.

272. Galileo's Telescope. — The earliest form of telescope was invented by Galileo. It produces an erect image by the use of a diverging lens for the eyepiece (Fig. 245).

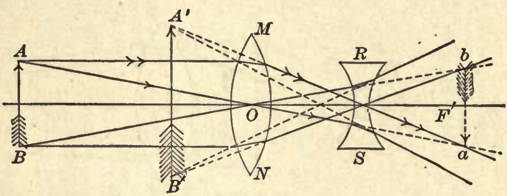


Fig. 245

This lens is placed between the objective and the real image, *ab*, which would be formed by the objective if the eyepiece were not interposed. Its focus is practically at the image *ab*, and the rays of light issue from it slightly divergent for distant objects. The image is therefore at $A'B'$ instead of at *ab*, and it is erect and enlarged. This telescope is much shorter than the astronomical telescope, for the distance between the lenses is the difference of their focal lengths instead of their sum. In the *opera glass* two of Galileo's telescopes are attached together with their axes parallel.

273. The Projection Lantern is an apparatus by which a greatly enlarged image of an object can be projected on a screen. The three essentials of a projection lantern are a strong light, a condenser, and an objective. The light may be the electric arc light, as shown in Fig. 246, the calcium light, or a large oil burner. The condenser *E* is

composed of a pair of converging lenses; its chief purpose is the collection of the light on the object by refraction, so as to bring as much as possible on the screen. The object *AB*, commonly a drawing or a photograph on glass, is placed near the condenser *SS*, where

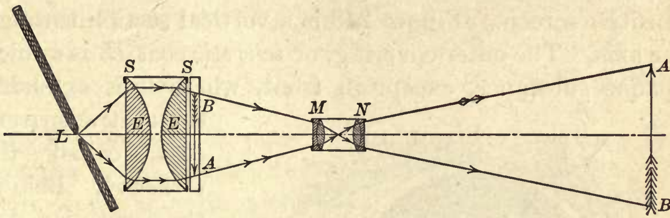


Fig. 246

it is strongly illuminated. The objective, *MN*, is a combination of lenses, acting as a single lens to project on the screen a real, inverted, and enlarged image of the object.

274. The Photographer's Camera consists of a box *LS* (Fig. 247), adjustable in length, blackened inside, and provided at one end with a lens or a combination of lenses, acting as a single one, and at the other with a holder for the sensitized plate.

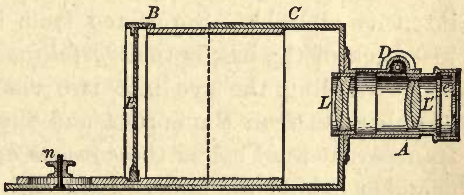


Fig. 247

If by means of a rack and pinion the lens *L'* be properly focused for an object in front of it, an inverted image will be formed on the sensitized plate *E*. The light acts on the salts contained in the sensitized film, producing in them a modification which, by the processes

of "developing" and "fixing," becomes a permanent negative picture of the object. When a "print" is made from this negative, the result is a positive picture.

275. The Eye. — The eye is like a small photographic camera, with a converging lens, a dark chamber, and a sensitive screen. Figure 248 is a vertical section through the axis. The outer covering, or *sclerotic* coat *H*, is a thick opaque substance, except in front, where it is extended as a transparent coat, called the *cornea A*. Behind the cornea is a diaphragm *D*, constituting the colored part of the eye, or the *iris*. The circular opening in the iris is the *pupil*, the size of which changes with the intensity of light. Supported from the walls of the eye, just back of the iris, is the *crystalline lens E*, a transparent body dividing the eye into two chambers; the anterior chamber between the cornea and the crystalline lens is a transparent fluid called the *aqueous humor*, while the large chamber behind the lens is filled with a jellylike substance called the *vitreous humor*. The *choroid coat* lines the walls of this posterior chamber, and on it is spread the *retina*, a membrane traversed by a network of nerves, branching from the *optic nerve M*. The choroid coat is filled with a black pigment, which serves to darken the cavity of the eye, and to absorb the light reflected internally.

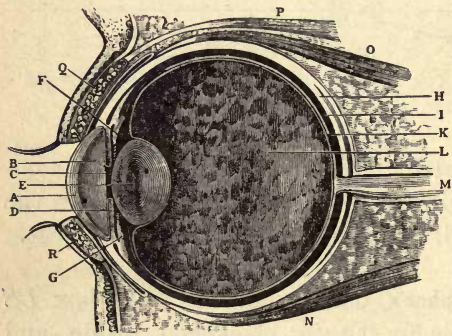


Fig. 248

276. Sight. — When rays of light diverge from the object and enter the pupil of the eye they form an inverted image on the retina (Fig. 249) precisely as in the photo-

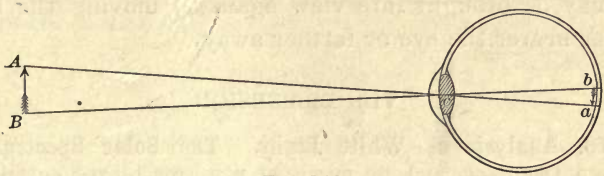


Fig. 249

graphic camera. In place of the sensitized plate is the sensitive retina, from which the stimulus is carried to the brain along the optic nerve.

In the camera the distance between the lens and the screen or plate must be adjusted for objects at different distances. In the eye the corresponding distance is fixed, and the adjustment for distinct vision is made by unconsciously changing the curvature of the front surface of the crystalline lens by means of the ciliary muscle *F*, *G* (Fig. 248). This capability of the lens of the eye to change its focal length for objects at different distances is called *accommodation.*

277. The Blind Spot. — There is a small depression where the optic nerve enters the eye. The rest of the retina is covered with microscopic rods and cones, but there are none in this depression, and it is insensible to light. It is accordingly called the *blind spot.* Its existence can be readily proved by the help of Fig. 250. Hold the book

Fig. 250

with the circle opposite the right eye. Now close the left eye and turn the right to look at the cross. Move

the book toward the eye from a distance of about a foot, and a position will readily be found where the black circle will disappear. Its image then falls on the blind spot. It may be brought into view again by moving the book either nearer the eye or farther away.

VII. DISPERSION

278. Analysis of White Light. The Solar Spectrum.—Darken the room, and by means of a mirror hinged outside the window, reflect a pencil of sunlight into the room. Close the opening in the window with a piece of tin, in which is cut a very narrow vertical slit. Let the ribbon of sunlight issuing from the slit be incident obliquely on a glass prism (Fig. 251). A many-colored band, gradually changing from red at one end through orange, yellow, green, blue, to violet at the other, appears on the screen. If a converging lens of about 30 cm. focal length be used to focus an image of the slit on the screen, and the prism be placed near the principal focus, the colored images of the slit will be more distinct.

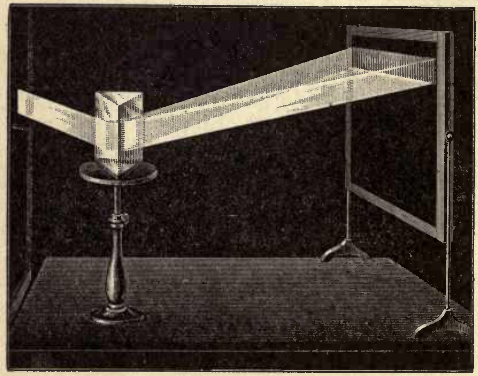


Fig. 251

This experiment shows that white or colorless light is a mixture of an infinite number of differently colored rays, of which the red is refracted least and the violet most. The brilliant band of light consists of an indefinite number of colored images of the slit; it is called the *solar spectrum*, and the opening out or separating of the beam of white light is known as *dispersion*.

279. Synthesis of Light. — Project a spectrum of sunlight on the screen. Now place a second prism like the first behind it, but reversed in position (Fig. 252). There will be formed a colorless image, slightly displaced on the screen.

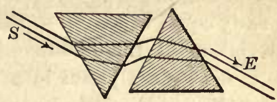


Fig. 252

The second prism reunites the colored rays, making the effect that of a thick plate of glass (§ 255). The recomposition of the colored rays into white light may also be effected by receiving them on a concave mirror or a large convex lens.

280. Chromatic Aberration. — Let a beam of sunlight into the darkened room through a round hole in a piece of cardboard. Project an image of this aperture on the screen, using a double-convex lens for the purpose. The round image will be bordered with the spectral colors.

This experiment shows that the lens refracts the rays of different colors to different foci. This defect in lenses is known as *chromatic aberration.* The violet rays, being more refrangible than the red, will have their focus nearer to the lens than the red, as shown in Fig. 253, where v is the principal focus for violet light and r for red. If a screen were placed at x, the image would be bordered with red, and if at y with violet.

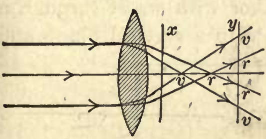


Fig. 253

281. The Achromatic Lens. — With a prism of crown glass project a spectrum of sunlight on the screen, and note the length of the spectrum when the prism is turned to give the least deviation (§ 256). Repeat the experiment with a prism of flint glass having the same refracting angle. The spectrum formed by the flint glass will be about twice as long as that given by crown

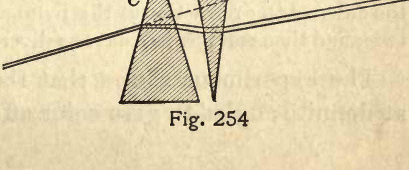


Fig. 254

glass, while the position of the middle of the spectrum on the screen is about the same in the two cases. Now use a flint glass prism whose refracting angle is half that of the crown glass one. The spectrum is nearly equal in length to that given by the crown glass prism, but the deviation of the middle of it is considerably less. Finally, place this flint glass prism in a reversed position against the crown glass one (Fig. 254). The image of the aperture is no longer colored, and the deviation is about half that produced by the crown glass alone.

Fig. 255

In 1757 Dollond, an English optician, combined a double-convex lens of crown glass with a plano-concave lens of flint glass so that the dispersion by the one neutralized that due to the other, while the refraction was reduced about half (Fig. 255). Such a lens or system of lenses is called *achromatic*, since images formed by it are not fringed with the spectral colors.

282. The Rainbow.— Cement a crystallizing beaker 12 or 15 cm. in diameter to a slate slab. Fill the beaker with water through a hole drilled in the slate. Support the slate in a vertical plane and direct a ribbon of white light upon the beaker at a point about 60° above its horizontal axis, as *SA* (Fig. 256). The light may be traced through the water, part of it issuing at the back at *B* as a diverging pencil, and a part reflected to *C* and issuing as spectrum colors along *CD*. If other points of incidence be tried, the colors given by the reflected portion are very indistinct except at 70° below the axis. After refraction at this point, the light is internally reflected twice and then emerges in front as a diverging pencil of spectrum colors.

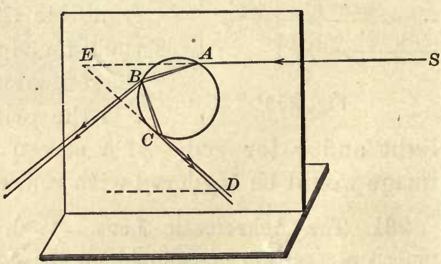


Fig. 256

The experiment shows that the light must be incident at definite angles to give color effects. The red constitu-

ent of white light incident at about 60° keeps together after reflection and subsequent refraction; that is, the red rays are practically parallel and thus have sufficient intensity to produce a red image. The same is true of the violet light incident at about 59° from the axis. The other spectral colors arrange themselves in order between the red and violet.

When sunlight falls in this manner on raindrops, they disperse the light and the spectral colors produced form the *rainbow*. Two bows are often visible, the *primary* and the *secondary*. The *primary bow* is the inner and brighter one formed by a single internal reflection; it is distinguished by being red on the outside and violet on the inside. The *secondary bow*, formed by two internal reflections, is fainter, and has the order of colors reversed. Figure 257 shows the relative position of the sun, the observer, and the raindrops which form the bows.

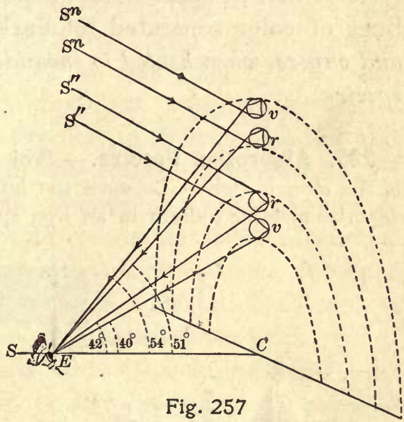


Fig. 257

283. Continuous Spectra. — Throw on a screen the spectrum of the electric arc, using preferably for the purpose a hollow prism filled with carbon bisulphide. The spectrum will be composed of colors from red at one end through orange, yellow, green, blue, and violet at the other without interruptions or gaps.

The experiment illustrates *continuous spectra*, that is, spectra without breaks or gaps in the color band. *Solids*,

liquids, and dense vapors and gases, when heated to incandescence, give continuous spectra.

284. Discontinuous Spectra. — Project on the screen the spectrum of the electric light. Place in the arc a few crystals of sodium nitrate. The intense heat will vaporize the sodium, and a spectrum will be obtained consisting of bright colored lines, one red, one yellow, three green, and one violet, the yellow being most prominent.

The experiment illustrates *discontinuous* or *bright line spectra*, that is, spectra consisting of one or more bright lines of color separated by dark spaces. *Rarefied gases and vapors, when heated to incandescence, give discontinuous spectra.*

285. Absorption Spectra. — Project on the screen the spectrum of the electric light. Between the lamp and the slit *S* (Fig. 258) vaporize metallic sodium in an iron spoon so placed that the white light passes through the heated sodium vapor before dispersion by the prism. A dark line will appear on the screen in the yellow of the spectrum at the place where the bright line was obtained in the preceding experiment.

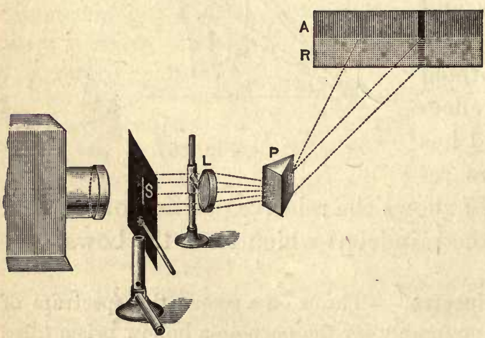


Fig. 258

The experiment illustrates an *absorption, reversed,* or *dark line spectrum.* The dark line is produced by the absorption of the yellow light by sodium vapor. *Gases and vapors absorb light of the same refrangibility as they emit at a higher temperature.*

286. The Fraunhofer Lines. — Show on the screen a carefully focused spectrum of sunlight. Several of the colors will appear crossed with fine dark lines (Fig. 259).

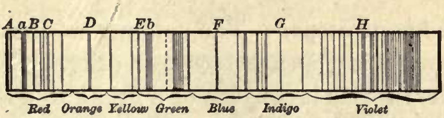


Fig. 259

Fraunhofer was the first to notice that some of these lines coincide in position with the bright lines of certain artificial lights. He mapped no less than 576 of them, and designated the more important ones by the letters *A*, *B*, *C*, *D*, *E*, *F*, *G*, *H*, the first in the extreme red and the last in the violet. For this reason they are referred to as the Fraunhofer lines. In recent years the number of these lines has been found to be practically unlimited.

In the last experiment it was shown that sodium vapor absorbs that part of the light of the electric arc which is of the same refrangibility as the light emitted by the vapor itself. Similar experiments with other substances show that every substance has its own absorption spectrum. These facts suggested the following explanation of the Fraunhofer lines: The heated nucleus of the sun gives off light of all degrees of refrangibility. Its spectrum would therefore be continuous, were it not surrounded by an atmosphere of metallic vapors and of gases, which absorb or weaken those rays of which the spectra of these vapors consist. Hence, the parts of the spectrum which would have been illuminated by those particular rays have their brightness diminished, since the rays from the nucleus are absorbed, and the illumination is due to the less intense light coming from the vapors. These absorption lines are

not lines of no light, but are lines of diminished brightness, appearing dark by contrast with the other parts of the spectrum.

287. The Spectroscope.—The commonest instrument for viewing spectra is the spectroscope (Fig. 260). In one of its simplest forms it consists of a prism *A*, a telescope *B*, and a tube called the *collimator C*, carrying an adjustable

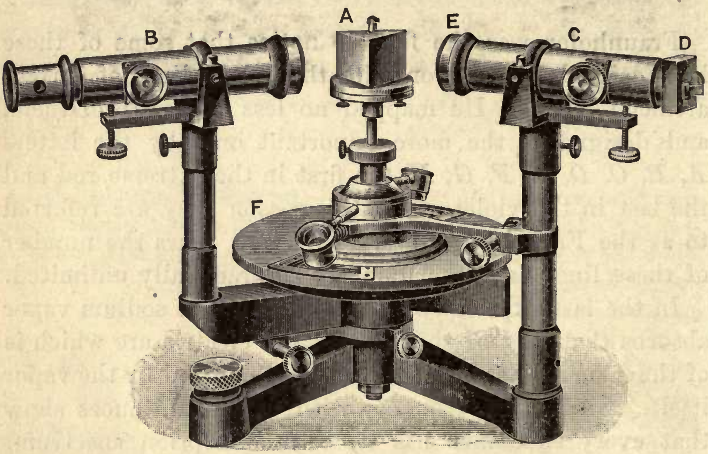


Fig. 260.

slit at the outer end *D*, and a converging lens at the other *E*, to render parallel the diverging rays coming from the slit. The slit must therefore be placed at the principal focus of the converging lens. To mark the deviation of the spectral lines, there is provided on the supporting table a divided circle *F*, which is read by the aid of verniers and reading microscopes attached to the telescope arm.

The applications of the spectroscope are many and various. By an examination of their absorption spectra, normal and diseased blood

are easily distinguished, the adulteration of substances is detected, and the chemistry of the stars is approximately determined. Figure 261 shows the agreement of a number of the spectral lines of iron with Fraunhofer lines in the solar spectrum; they indicate the presence of iron vapor in the atmosphere of the sun.

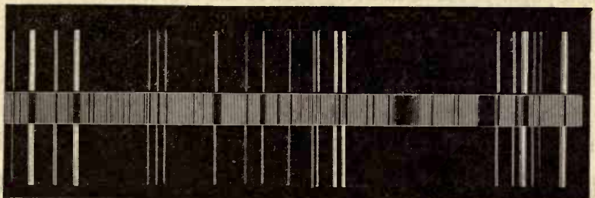


Fig. 261

VIII. COLOR

288. The Wave Length of light determines its color. Extreme red is produced by the longest waves, and extreme violet by the shortest. The following are the wave lengths for the principal Fraunhofer lines in air at 20° C. and 760 mm. pressure : —

A	Dark Red .	0.0007621 mm.	E_1	Light Green	0.0005270 mm.
B	Red . . .	6884 mm.	E_2	. . . . .	5269 mm.
C	Orange . .	6563 mm.	F	Blue . . .	4861 mm.
D_1	Yellow . .	5896 mm.	G	Indigo . .	4293 mm.
D_2	. . . . .	5890 mm.	H_1	Violet . .	3968 mm.

In white light the number of colors is infinite, and they pass into one another by imperceptible gradations of shade and wave length. Color stands related to light in the same way that pitch does to sound. In most artificial lights certain colors are either feeble or wanting. Hence, artificial lights are not generally white, but each one is characterized by the color that predominates in its spectrum.

289. Color of Opaque Bodies. — Project the solar spectrum on a white screen. Hold pieces of colored paper or cloth successively in different parts of the spectrum. A strip of red flannel appears brilliantly red in the red part of the spectrum, and black elsewhere; a blue ribbon is blue only in the blue part of the spectrum, and a piece of black paper is black in every part of the spectrum.

The experiment shows that the color of a body is due both to the light that it receives and the light that it reflects; that a body is red because it reflects chiefly, if not wholly, the red rays of the light incident upon it, the others being absorbed wholly or partly at its surface. It cannot be red if there is no red light incident upon it. In the same way a body is white if it reflects all the rays in about equal proportions, provided white light is incident upon it. So it appears that bodies have no color of their own, since they exhibit no color not already present in the light which illuminates them. This truth is illustrated by the difficulty experienced in matching colors by artificial lights, and by the changes in shade some fabrics undergo when taken from sunlight into gaslight. Most artificial lights are deficient in blue and violet rays; and hence all complex colors, into which blue or violet enters, as purple and pink, change their shade when viewed by artificial light.

290. Color of Transparent Bodies. — Throw the spectrum of the sun or of the arc light on the screen. Hold across the slit a flat bottle or cell filled with a solution of ammoniated oxide of copper.[1] The spectrum below the green will be cut off. Substitute a solution of picric acid, and the spectrum above the green will be cut off. Place both solutions across the slit and the green alone remains. It is the only color transmitted by both solutions. In like manner, blue glass cuts off the less refrangible part of the spectrum, ruby glass cuts off the more refrangible, and the two together cut off the whole.

[1] It is prepared by adding ammonia to a solution of copper sulphate, until the precipitate at first formed is dissolved.

This experiment shows that the color of a transparent body is determined by the colors that it absorbs. It is colorless like glass if it absorbs all colors in like proportion, or absorbs none; but if it absorbs some colors more than others, its color is due to the mixed impression produced by the various colors passing through it.

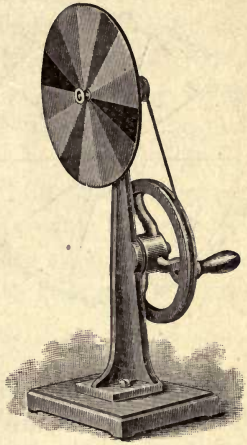


Fig. 262

291. Mixing Colored Lights. — Out of colored papers cut several disks, about 15 cm. in diameter, with a hole at the center for mounting them on the spindle of a whirling machine (Fig. 262), or for slipping them over the handle of a heavy spinning top. Slit them along a radius from the circumference to the center, so that two or more of them can be placed together, exposing any proportional part of each one as desired (Fig. 263). Select seven disks, whose colors most nearly represent those of the solar spectrum; put them together so that equal portions of the colors are exposed. Clamp on the spindle of the whirling machine and rotate them rapidly. When viewed in a strong light the color is an impure white or gray.

This method of mixing colors is based on the physiological fact that a sensation lasts longer than the stimulus producing it. Before the sensation caused by one stimulus has ceased, the disk has moved, so that a different impression is produced. The effect is equivalent to superposing the several colors on one another at the same time.

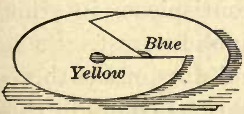


Fig. 263

292. Three Primary Colors. — If red, green, and blue, or violet disks are used, as in § 291, exposing equal portions, gray or impure white is obtained when they are rapidly rotated. If any two colors standing opposite each other in Fig. 264 are used, the result is white; and if any two alternate ones are used, the result is the intermediate one. By using the red, the green, and the violet disks, and exposing in different proportions, it has been found possible to produce any color of the spectrum. This fact suggested to Dr. Young the theory that there are only three primary color sensations, and that our recognition of different colors is due to the excitation of these three in varying degrees.

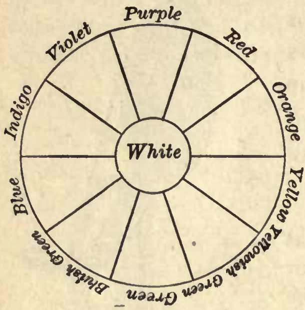


Fig. 264

The color top is a standard toy provided with colored paper disks, like those of Fig. 262. When red, green, and blue disks are combined so as to show sectors of equal size, the top, when spinning in a strong light, appears to be gray. Gray is a white of low intensity. The colors of the disks are those of pigments, and they are not pure red, green, and blue.

293. Three-color Printing. — The frontispiece in this book illustrates a three-color print of much interest. Such a print is made up of very fine lines and dots of the three pigments, red, yellow, and blue; the various colors in the picture are mixtures of these three with the white of the paper. The greens come chiefly from the overlapping and mixture of the yellow and blue pigments.

The process is briefly as follows: Three negatives of the same original are taken through transparent screens of red, green, and blue, and each is crossed by fine lines or dots. Copper plates are made from the negatives, and each plate is inked for printing with an ink of a color which gives white, when mixed with the color of the screen through which the negative was taken. Thus, the plate made with the red screen is printed with greenish blue ink; those taken with the green and blue or violet screens are printed with crimson, red, or yellow ink, respectively. In the frontispiece the first plate was printed with yellow, the second with yellow and then with red, and the third with all three.

294. Complementary Colors. — *Any two colors whose mixture produces on the eye the impression of white light are called complementary.* Thus, red and bluish green are complementary; also orange and light blue. When complementary colors are viewed next to each other, the effect is a mutual heightening of color impressions.

Complementary colors may be seen by what is known as retinal fatigue. Cut some design out of paper, and paste it on red glass. Project it on a screen in a dark room. Look steadily at the screen for several seconds, and then turn up the lights. The design will appear on a pale green ground.

This experiment shows that the portion of the retina on which the red light falls becomes tired of red, and refuses to convey as vivid a sensation of red as of the other colors, when less intense white light is thrown on it. But it retains its sensitiveness in full for the rest of white light, and therefore conveys to the brain the impression of white light with the red cut out; that is, of the complementary color, green.

295. Mixing Pigments. — Draw a broad line on the blackboard with a yellow crayon. Over this draw a similar band with a blue crayon. The result will be a band distinctly green.

The yellow crayon reflects green light as well as yellow, and absorbs all the other colors. The blue crayon reflects green light along with the blue, absorbing all the others. Hence, in superposing the two chalk marks, the mixture absorbs all but the green. The mark on the board is green, because that is the only color that survives the double absorption. In mixing pigments, the resulting color is the residue of a process of successive absorptions. If the spectral *colors*, blue and yellow, are mixed, the product is white instead of green. So we see that a mixture of colored lights is a very different thing from a mixture of pigments.

IX. INTERFERENCE AND DIFFRACTION

296. Newton's Rings. — Press together at their center two small pieces of heavy plate glass, using a small iron clamp for the purpose. Then look obliquely at the glass; curved bands of color may be seen surrounding the point of greatest pressure.

This experiment is like one performed by Newton while attempting to determine the relation between the colors in the soap bubble and the thickness of the film. He used a plano-convex lens of long focus resting on a plate of plane glass. Figure 265 shows a section of the apparatus. Between the lens and the plate there is a wedge-shaped film of air, very thin, and quite similar to that formed between the glass plates in the above experiment.

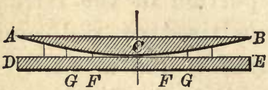


Fig. 265

If the glasses are viewed by reflected light, there is a dark spot at the point of contact, surrounded by several colored rings (Fig. 266); but if viewed by transmitted light, the colors are complementary to those seen by reflection (§ 294). The explanation is to be found in the interference of two sets of waves, one reflected internally from the curved surface *ACB*, and the other from the surface *DCE*, on which it presses. If light of one color is incident on *AB*, a portion will be reflected from *ACB*, and another portion from *DCE*. Since the light reflected from *DCE* has traveled farther by twice the thickness of the air film than that from *ACB*, and the film gradually increases in thickness from *C* outward, it follows that at some places the two reflected portions will meet in like phase, and at others in opposite phase, causing a strengthening of the light at the former, and extinction of it at the latter. If red light be used, the appearance will be that of a series of concentric circular red bands separated by dark ones, each shading off into the other. If violet light be employed, the colored bands will be closer together on account of the shorter wave length. Other colors will give bands intermediate in diameter between the red and violet. From this it follows that if the glasses be illuminated by white light, at every point some one color will be destroyed. The other colors will be either weakened or strengthened, depending on the thickness of the air film at the point under consideration, the color at each point being the result of mixing a large number of colors in unequal proportions. Hence,

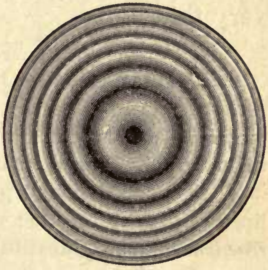


Fig. 266

the point C will be surrounded by a series of colored bands.[1]

The colors of the soap bubble, of oil on water, of heated metals which easily oxidize, of a thin film of varnish, and of the surface of very old glass, are all caused by the interference of light reflected from the two surfaces of a very thin film.

297. Diffraction. — Place two superposed pieces of perforated cardboard in front of the condenser of the projection lantern. The projected images of the very small holes, as one piece is moved across the other, are fringed with the spectral colors.

With a fine diamond point rule a number of equidistant parallel lines very close together on glass. They compose a transparent *diffraction grating.* Substitute this for the prism in projecting the spectrum of sunlight or of the arc light on the screen (§ 278). There will be seen on the screen a central image of the slit, and on either side of it a series of spectra. Cover half of the length of the slit with red glass and the other half with blue. There will now be a series of red images and also a series of blue ones, the red ones being farther apart than the blue. Lines ruled close together on smoked glass may be used instead of a "grating."

These experiments illustrate a phenomenon known as *diffraction.* The colored bands are caused by the interference of the waves of light which are propagated in all directions from the fine openings. The effects are visible because the transparent spaces are so small that the intensity of the direct light from the source is largely reduced. Diffraction gratings are also made to operate by reflecting light. Striated surfaces, like mother-of-pearl, changeable

[1] The light from ACB differs in phase half a wave length from that reflected from DE, because the former is reflected in an optically dense medium next to a rare one, and the latter in an optically rare medium next to a dense one. This phase difference is additional to the one above described.

silk, and the plumage of many birds, owe their beautiful changing colors to interference of light by diffraction.

Questions

1. Why is the flint glass of an achromatic lens the diverging part of the combination instead of the converging?

2. Why is the rainbow circular?

3. Do different persons see the same rainbow?

4. Why is the rainbow not seen at midday?

5. In projecting pictures on a screen, why should the screen be white?

6. Of which case of images by lenses is the projecting lantern an application?

7. In enlarging a negative by photography where must the negative be placed with respect to the lens?

8. Why do flowers that are purple by sunlight look red by lamplight?

9. Account for the color on a plate of glass when it is brushed over with alcohol.

10. Account for the crossed bands of colors seen by looking through a silk umbrella at an arc electric light.

CHAPTER IX

HEAT

I. HEAT AND TEMPERATURE

298. Nature of Heat. — For a long time it was believed that heat was a subtle and weightless fluid that entered bodies and possibly combined with them. This fluid was called *caloric*. About the beginning of the last century certain experiments of Count Rumford and Sir Humphry Davy demonstrated that the caloric theory of heat was no longer tenable; and finally about the middle of the century, when Joule proved that a definite amount of mechanical work is equivalent to a definite amount of heat, it became evident that *heat is a form of molecular energy*.

The modern *kinetic* theory, briefly stated, is as follows: The molecules of a body have a certain amount of independent motion, generally very irregular. Any increase in the energy of this motion shows itself in additional warmth, and any decrease by the cooling of the body. The heating or the cooling of a body, by whatever process, is but the transference or the transformation of energy.

299. Temperature. — If we place a mass of hot iron in contact with a cold one, the latter becomes warmer and the former cooler, the heat flowing from the hot body to the

cold one. The two bodies are said to differ in *temperature* or "heat level," and when they are brought in contact there is a flow of heat from the one of higher temperature to the one of lower till thermal (heat) equilibrium is established. *Temperature* is the thermal condition of a body which determines the transfer of heat between it and any body in contact with it. This transfer is always from the body of higher temperature to the one of lower. Temperature is a measure of the degree of hotness; it depends solely on the kinetic energy of the molecules of the body. Temperature must be distinguished from quantity of heat. The water in a pint cup may be at a much higher temperature than the water in a lake, yet the latter contains a vastly greater quantity of heat, owing to the greater quantity of water.

300. Measuring Temperature. — Fill three basins with moderately hot water, cold water, and tepid water respectively. Hold one hand in the first, and the other in the second for a short time; then transfer both quickly to the tepid water. It will feel cold to the hand that has been in hot water and warm to the other. Hold the hand successively against a number of the various objects in the room, at about the same height from the floor. Metal, slate, or stone objects will feel colder than those of wood, even when side by side and of the same temperature.

These experiments show that the sense of touch does not give accurate information regarding the relative temperature of bodies, and some other method must be resorted to for reliable measurement. The one most extensively used is based on the regular increase in the volume of a body attending a rise in its temperature. This method is illustrated by the common mercurial thermometer.

II. THE THERMOMETER

301. The Thermometer. — The common *mercurial thermometer* consists of a capillary glass tube of uniform bore, on one end of which is blown a bulb, either spherical or cylindrical (Fig. 267). Part of the air is expelled by heating, and while in this condition the open end of the tube is dipped into a vessel of pure mercury. As the tube cools, mercury is forced into the tube by atmospheric pressure. Enough mercury is introduced to fill the bulb and part of the tube at the lowest temperature which the thermometer is designed to measure. Heat is now applied to the bulb till the expanded mercury fills the tube; the end is then closed in the blowpipe flame. The mercury contracts as it cools, leaving a vacuum at the top of the tube.

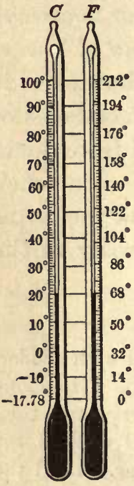


Fig. 267

302. Necessity of Fixed Points. — No two thermometers are likely to have bulbs and stems of the same capacity. Consequently, the same increase of temperature will not produce equal changes in the height of the mercury. If, then, the same scale were attached to all thermometers, their indications would differ so widely that the results would be worthless. Hence, if thermometers are to be compared, corresponding divisions on the scale of different instruments must indicate the same temperature. This may be done by graduating every thermometer by comparison with a standard, an expensive proceeding and for many purposes unnecessary, since mercury has a nearly uniform rate of expansion. If two points are marked on the stem, the others can be obtained by dividing the space between

them into the proper number of equal parts. Investigations have made it certain that under a constant pressure the temperature of *melting ice* and that of *steam* are invariable. Hence, the *temperature of melting ice* and *that of steam* under a pressure of 76 cm. of mercury (one atmosphere) have been chosen as the fixed points on a thermometer.

303. Marking the Fixed Points. — The thermometer is packed in finely broken ice, as far up the stem as the mercury extends. The containing vessel (Fig. 268) has an opening at the bottom to let the water run out. After standing in the ice for several minutes the top of the thread of mercury is marked on the stem. This is called the *freezing point.*

Fig. 268

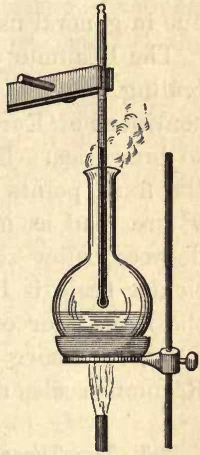


Fig. 269

The *boiling point* is marked by observing the top of the mercurial column when the bulb and stem are enveloped in steam (Fig. 269) under an atmospheric pressure of 76 cm. (29.92 in.). If the pressure at the time is not 76 cm., then a correction must be applied, the amount being determined by the approximate rule that the temperature of steam rises 0.1° C. for every increase of 2.71 mm. in the barometric reading, near 100° C.

304. Thermometer Scales. — The distance between the fixed points is divided into equal parts called *degrees.* The number of such parts is wholly arbitrary, and several different scales have been introduced. Three of these are in use at the present time: the *Fahrenheit*, the *Centi-*

grade, and the *Réaumur*. The Fahrenheit scale was introduced by Fahrenheit about 1714, and is the one in common use in all English-speaking countries. For some unknown reason he marked the freezing point at 32° above the zero of the scale, and the boiling point at 212°, dividing the space between into 180 equal parts.

The Centigrade scale was designed by Celsius about 1742. It differs from the Fahrenheit in making the freezing point 0° and the boiling point 100°, the space between being divided into 100 equal parts. This is the one in general use among scientific men.

The Réaumur scale marks the freezing point 0° and the boiling point 80°. This is the household scale on the continent of Europe; in this country its use is restricted to breweries. Each of these scales is extended beyond the fixed points as far as desired. The divisions below 0° are read as negative; for example, − 10° signifies 10 degrees below zero. The reading according to any particular scale is indicated by affixing the initial letter of the name; for example, 5° F., 5° C., and 5° R. signify 5 degrees above zero on the Fahrenheit, Centigrade, and Réaumur scales respectively.

305. The Three Scales Compared. — In Fig. 270 AB is a thermometer with three scales attached, P is the head of the mercury column, and F, C, and R are the readings on the scales respectively. On the Fahrenheit scale $AB = 180$ and $AP = F - 32$, since the zero is 32 spaces below A; on the Centigrade $AB = 100$ and $AP = C$; on the

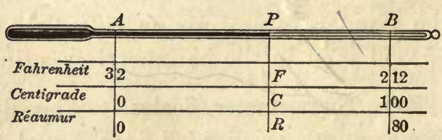


Fig. 270.

Réaumur $AB = 80$ and $AP = R$. Then the ratio of AP to AB is $\frac{F-32}{180} = \frac{C}{100} = \frac{R}{80}$. By substituting the reading on any one scale in this equation the equivalent on either of the other scales is easily obtained. For example, if it is required to express 68° F. on the Centigrade scale, then $\frac{68-32}{180} = \frac{C}{100}$; whence $C = 20°$.

100 × x − 32 = 68 × 1

100x −

306. Limitations of the Mercurial Thermometer. — As mercury freezes at − 38.8° C., it cannot be used as the thermometric substance below this temperature. For temperatures below − 38° C. alcohol is substituted for mercury. Under a pressure of one atmosphere mercury boils at about 350° C. For temperatures approaching this value and up to about 550° C. the thermometer stem is filled with pure nitrogen under pressure. The pressure of the gas keeps the mercury from boiling (§ 331).

Fig. 271

307. The Clinical Thermometer. — The clinical thermometer is a sensitive instrument of short range for indicating the temperature of the human body. It is usually graduated from 95° to 110° F., or from 35° to 45° C. There is a constriction in the tube just above the bulb (Fig. 271), which causes the thread of mercury to break at that point when the temperature begins to fall, leaving the top of the separated thread to mark the highest temperature registered. A sudden jerk or tapping of the thermometer forces the mercury down past the constriction and sets it for a new reading.

Questions and Problems

1. Why should the tube of a thermometer be of uniform bore?

2. Is it correct to speak of one temperature as twice that of another?

3. Why may thermometers differ in length and still measure between the same extremes of temperature?

4. Why do thermometers have a bulb on one end? Would a closed uniform tube answer just as well?

5. What would be the effect on the indications of a thermometer if the glass expanded the same as the mercury?

6. Convert into equivalent readings on the Centigrade scale: 98° F., – 40° F., 68° F.

7. Convert into equivalent readings on the Fahrenheit scale: 36° C., – 40° C., 29° C.

8. The lowest temperature yet obtained is claimed to be – 271.3° C. What would this be on the Fahrenheit scale?

9. The melting points of iron and copper are 2737° F. and 1943° F. respectively. Express these temperatures in Centigrade degrees.

10. A correct Fahrenheit thermometer registers the temperature of a room as 70°; a faulty Centigrade thermometer reads 20°. Find the error of the latter.

11. When the barometric pressure is 74 cm., what is the boiling point?

12. A certain Centigrade thermometer registers 2° in melting ice and 100° in steam under normal atmospheric pressure. What is the correct value of a temperature of 25° as given by this instrument?

III. EXPANSION

308. Expansion of Solids. — Insert a long knitting needle *A* in a block of wood so as to stand vertically (Fig. 272). A second needle *D* is supported parallel to the first by means of a piece of cork or wood *C*. The lower end of *D* just touches the mercury in the cup *H*. An electric circuit is made through the mercury, the needle,

an electric battery, and the bell *B*, as shown. Now apply a Bunsen flame to *A*; *D* will be lifted out of the mercury and the bell will stop ringing. Then heat *D* or cool *A*, and the contact of *D* with the mercury will be renewed as shown by the ringing of the bell.

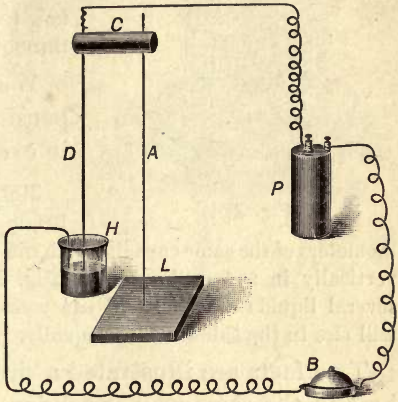


Fig. 272

This experiment shows that solids expand in length when heated and contract when cooled. To this rule of expansion there are a few exceptions, notably iodide of silver and stretched india-rubber.

Rivet together at short intervals a strip of sheet copper and one of sheet iron *D* (Fig. 273). Support this compound bar so as to play between two points *A* and *C*, which are connected through the battery *P* and the bell *B*. Apply a Bunsen flame to the bar. It will warp, throwing the top over against either *A* or *C*, and will cause the bell to ring.

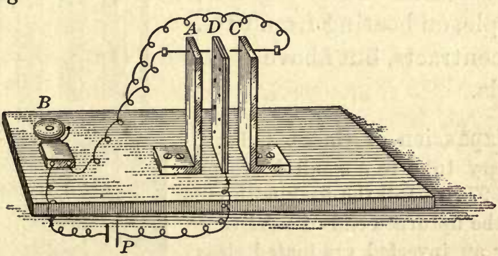


Fig. 273

The experiment shows that the two metals expand unequally and cause the bar to warp.

Figure 274 illustrates a piece of apparatus known as Gravesande's ring. It consists of a metallic ball that at ordinary temperatures will just pass through the ring. Heat the ball in boiling water. It will now rest on the ring and will not fall through until it has cooled.

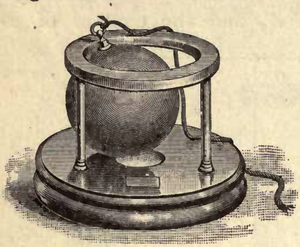


Fig. 274

We conclude that the expansion of a solid takes place in every direction.

309. Expansion of Liquids. — Partly fill several small air thermometers of the same capacity with different liquids, and support them vertically in a metallic vessel (Fig. 275). Note the height of the several liquids and then fill the vessel with hot water. The liquids will rise in the tubes but not equally.

Two facts are illustrated: first, liquids are affected by heat in the same way as solids; second, the expansion of the liquids is greater than that of the glass or there would be no apparent increase in their volume.

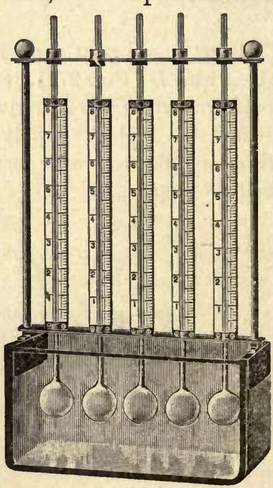


Fig. 275

Some liquids do not expand when heated at certain points on the thermometric scale. Water, for example, on heating from 0° C. to 4° C. contracts, but above 4° C. it expands.

310. Expansion of Gases. — Fit a bent delivery tube to a small Florence flask (Fig. 276). Fill the flask with air and place the upturned end of a delivery tube under an inverted graduated glass cylinder filled with water. Heat the flask by immersing it in a vessel of moderately hot water. The air will expand and escape through the delivery tube into the cylinder; note the amount. Now refill

the flask with some other gas, as coal gas, and repeat the experiment. The amount of gas collected will be nearly the same.

Investigation has shown that all gases which are hard to liquefy expand very nearly alike at atmospheric pressure, approaching equality as the pressure is diminished. Gases that are easily liquefied, as carbon dioxide, show the largest variation in their expansion.

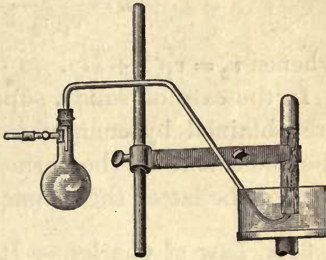


Fig. 276

311. Coefficients of Expansion. — It appears from the preceding experiments that substances when heated expand in every direction. This expansion in volume is called *cubical expansion*, in distinction from *linear expansion*, or expansion in length, and *superficial expansion*, or expansion in area. The *coefficient of linear expansion* is the fraction of its length which a body expands when heated from 0° C. to 1° C.; the *coefficient of superficial expansion* is the fraction of its area which a body expands when heated from 0° C. to 1° C.; and the *coefficient of cubical expansion* is the fraction of its volume which a body expands when heated from 0° C. to 1° C. Since the linear expansion of most substances is found to be nearly constant for each degree of temperature, it is customary to determine the average coefficient for a change of several degrees. If l_1 and l_2 represent the lengths of a metallic rod at the temperatures t_1 and t_2 respectively, then $\frac{l_2 - l_1}{t_2 - t_1} = \frac{l_2 - l_1}{t}$ is the expansion for 1°, in which t is the difference of temperatures. If a represents the average coefficient of expansion, then $a = \frac{l_2 - l_1}{l_1 t}$; whence

$l_2 = l_1(1 + at)$. In like manner for volumes, if k is the coefficient of cubical expansion, v_1 and v_2 the volumes at the temperatures t_1 and t_2 respectively, then

$$k = \frac{v_2 - v_1}{v_1(t_2 - t_1)} = \frac{v_2 - v_1}{v_1 t};$$

whence $v_2 = v_1(1 + kt)$.

In the case of solids, superficial and cubical expansion are obtained by computation from the linear expansion, the coefficient of the former being twice the linear, and that of the latter three times.

312. Law of Charles. — It was shown by Charles, in 1787, that the volume of a given mass of any gas under constant pressure increases by a constant fraction of its volume at zero for each rise of temperature of 1° C. The investigations of Regnault and others show that the law is not rigorously true, and that the accuracy of Charles's law is about the same as that of Boyle's law. The coefficient of expansion k of dry air is 0.003665, or about $\frac{1}{273}$. This fraction may be considered as the coefficient of expansion of any true gas.

313. The Absolute Scale. — The law of Charles leads to a fourth scale of temperature called the *absolute scale*. By this law the volumes of any mass of gas, under constant pressure, at 0° C., and at any other temperature t° C., are connected by the following relations (§ 311): —

$$v = v_0(1 + \tfrac{1}{273}t) = \frac{v_0(273 + t)}{273}. \quad \quad (a)$$

At any other temperature, t', the volume becomes

$$v' = \frac{v_0(273 + t')}{273}. \quad \quad (b)$$

Divide (a) by (b) and

$$\frac{v}{v'}=\frac{273+t}{273+t'}.$$

Suppose now a new scale is taken, whose zero is 273 Centigrade divisions below the freezing point of water, and that temperatures on this scale are denoted by T. Then $273+t$ will be represented by T, and $273+t'$ by T', and

$$\frac{v}{v'}=\frac{273+t}{273+t'}=\frac{T}{T'},$$

or *the volumes of the same mass of gas under constant pressure are proportional to the temperatures on this new scale.* The point 273° below 0° C. is called the *absolute zero*, and the temperatures on this scale, *absolute temperatures.* Up to the present it has not been found possible to cool a body to the absolute zero; but by evaporating liquid hydrogen under very low pressure, a temperature estimated to be within 9° of the absolute zero has been obtained by Professor Dewar; and Professor Onnes, by liquefying helium, believes that he obtained a temperature within 3° of the absolute zero.

314. The Laws of Boyle and Charles Combined. — If v, p, and T denote the volume, pressure, and absolute temperature of a given mass of gas, then by Boyle's law (§ 74) $v \propto \frac{1}{p}$, when T is constant; and by the law of Charles, $v \propto T$, when p is constant. Therefore when T and p both vary, v varies directly as T and inversely as p, or $v \propto \frac{T}{p}$. Whence $pv \propto T$, or $pv = \text{constant} \times T$. This

relation is known as the "gas equation" and is written

$$pv = RT. \quad . \quad . \quad . \text{ (Equation 33)}$$

R is the constant which converts a proportionality into an equality. It follows that not only is the volume of a given mass of gas under constant pressure proportional to its absolute temperature (§ 313), but the product of the pressure and volume of a given mass of gas is proportional to its absolute temperature.

To illustrate the use of the above relation: If 20 cm.^{3} of gas at 20° C. is under a pressure of 76 cm. of mercury, what will be the pressure when its volume is 30 cm.^{3} and temperature 50° C.?

From equation (33), $\frac{pv}{T}$ is a constant,

or $$\frac{pv}{T} = \frac{p'v'}{T'}.$$

Hence $$\frac{76 \times 20}{273 + 20} = \frac{p \times 30}{273 + 50},$$

from which $$p = 55.85 \text{ cm.}$$

315. Force of Contraction and Expansion. — Fill a small test tube about one quarter full of water, and close the end by fusion. Lay it in an empty sand bath on the ring of an iron stand. Apply heat, and stand at a safe distance. In a few minutes there will be a loud report, caused by the bursting of the tube.

The force of expansion or of contraction of a subtance is evidently equal to the force necessary to compress or expand it to the same extent by mechanical means, and hence can be computed by proceeding in the manner illustrated in the following example: A bar of malleable iron, one square inch in cross-sectional area, if placed under the tension of a ton, increases in length 0.0001 of itself.

The coefficient of linear expansion of iron is 0.0000122. Since $0.0001 \div 0.000122 = 8+$, a change of temperature of about 8° C. will produce the same change in the length of the bar as a force of one ton.

It takes a pressure of 600 atmospheres to keep mercury from expanding when heated from 0° C. to 10° C.

316. Applications of Expansion and Contraction. — Many familar phenomena are accounted for by expansion or contraction attending changes of temperature. If hot water is poured into a thick glass tumbler, the glass will probably break because of the stress produced by the sudden expansion of its inner surface. The principle of unequal expansion is employed in thermometers, in the compensated clock pendulum and in the balance wheel of a watch (Fig. 277), in which the rim is made in two sections, each composed of two metals soldered together side by side, with the more expansible metal on the outside. When the temperature rises, the ends a, a' move inward. Glass and platinum have nearly the same coefficient of expansion. For that reason platinum is in great demand in the manufacture of incandescent electric lamps, since it does not crack the glass when it cools. Iron tires are fitted to wheels and then expanded by heating so that they slip on easily; on cooling, they contract and compress the wheel. The rivets which hold together the plates of steam boilers are inserted red-hot, and hammered down. The contracting rivets press the plates together with great force. In all heavy iron structures, such as railroad bridges, a certain freedom of motion of the parts

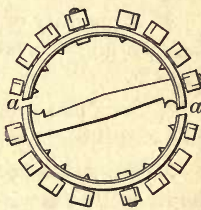


Fig. 277

must be provided for; otherwise, the changes in length attending variations in temperature would have a disastrous effect. Sidewalks of artificial stone should have spaces left for expansion to prevent "buckling." Crystalline rocks, on account of unequal expansion in different directions, are slowly disintegrated by changes of temperature; and for the same reason quartz crystals, when strongly heated, fly in pieces.

Questions and Problems

1. What is the objection in stringing telegraph wires in the summer time to stretching them tight?

2. Why will warming the neck of a bottle often loosen a glass stopper that has stuck?

3. A quantity of alcohol that measures 20 gallons on the first of January might measure as much as 21 gallons on the first of July. Explain.

4. Set a pan even full of cold water on a hot stove. In a short time it will begin to overflow. Why?

5. Fill a vessel containing a piece of ice level full of water. When the ice melts the water level neither rises nor falls. Why?

6. An iron rod 60 cm. long at 20° C. was 60.055 cm. long at 95° C. Calculate the coefficient of expansion.

7. A brass rod was 100 cm. long at 20° C. What will be its length at 0° C., if the coefficient of linear expansion is 0.0000186?

8. A copper bar 62.5 cm. long at 5° C. expands by 1.1 mm. when heated to 98° C. Find its coefficient of expansion.

9. An iron bridge is 300 ft. long. Calculate the variation in length it will undergo between the temperatures − 10° C. and 40° C., the coefficient of expansion of iron being 0.0000122.

10. A glass graduate holds one liter at 15° C. How much will it hold at 25° C., if the coefficient of cubical expansion is 0.000025?

11. Two metal bars are each one meter long at 10° C. How much will they differ in length at 40° C. if one is steel (coefficient of

linear expansion, 0.0000132) and the other aluminum (coefficient, 0.0000222)?

12. If 1500 cm.^{3} of air at 15° C. be changed in temperature to 50° C., what will the volume be if the pressure is constant?

13. In an experiment to determine the coefficient of expansion of air the following data were obtained: Volume of air at 0° C., 145 cm.^{3}; at 100° C., 198 cm.^{3}, the pressure remaining the same. Calculate the coefficient of expansion.

14. A flask filled with air at 20° C. and under 75 cm. pressure is stoppered and heated to 70° C. Assuming that the flask does not expand appreciably, under what pressure will the air be?

15. If a liter of dry air at 0° C. weighs 1.3 gm., how many liters will weigh 10 gm. if the pressure be reduced to one half and the temperature be raised to 100° C.?

IV. MEASUREMENT OF HEAT

317. The Unit of Heat. — The unit of heat in the *c. g. s.* system is the *calorie.* It is defined as *the quantity of heat that will raise the temperature of one gram of water one degree Centigrade.* There is no agreement as to the position of the one degree on the thermometric scale, although it is known that the unit quantity of heat varies slightly at different points on the scale. If the degree interval chosen is from 15° to 16° C., the calorie is then the one hundredth part of the heat required to raise the temperature of one gram of water from 0° to 100° C.

In engineering practice in England and America the British thermal unit (B. T. U.) is commonly employed. It is the heat required to raise the temperature of one pound of water one degree Fahrenheit.

318. Thermal Capacity. — The *thermal capacity* of a body is the number of calories required to raise its temperature one degree Centigrade. The thermal capacity of equal

masses of different substances differs widely. For example, if 100 gm. of water at 0° C. be mixed with 100 gm. at 100° C., the temperature of the whole will be very nearly 50° C. But if 100 gm. of copper at 100° C. be cooled in 100 gm. of water at 0° C., the final temperature will be about 9.1° C. The heat lost by the copper in cooling through 90.9° is sufficient to heat the same mass of water only 9.1°, that is, the thermal capacity of water is about ten times as great as that of an equal mass of copper.

319. Specific Heat. — The *specific heat* of a substance is the number of calories of heat required to raise the temperature of one gram of it through one degree Centigrade. It may be defined independently of any temperature scale as the ratio between the number of units of heat required to raise the temperature of equal masses of the substance and of water through one degree. The specific heat of mercury is .033, that is, the heat that will raise 1 gm. of mercury through 1° C. will raise 1 gm. of water through only 0.033° C.

320. Numerical Problem in Specific Heat. — The principle applied in the solution of such problems is that the gain or loss of heat by the water is equal to the loss or gain of heat by the body introduced into the water. The gain or loss of heat by the body is equal to the product of its mass, its specific heat, and its change of temperature.

To illustrate: 20 gm. of iron at 98° C. are placed in 75 gm. of water at 10° C. contained in a copper beaker weighing 15 gm., specific heat 0.095. The resulting temperature of the water and the iron is 12.5° C. Find the specific heat of iron.

The thermal capacity of the beaker is $15 \times 0.095 = 1.425$ calories. The heat lost by the iron is $20 \times s \times (98 - 12.5)$ calories, in which s represents the specific heat of iron, and $(98 - 12.5)$ its change of temperature. The heat gained by the water and the copper vessel is $(75 + 1.425) \times (12.5 - 10)$ calories; the second factor is the gain in temper-

ature of the water and the beaker. It follows by equating these two quantities that $20 \times s \times (98 - 12.5) = (75 + 1.425) \times (12.5 - 10)$. Solving for s, we have $s = 0.112$ calorie per gram.

Questions and Problems

1. If water were used as the substance in a thermometer, what would be the lowest temperature it would register?

2. Give three reasons why mercury is a more suitable substance for thermometers than water.

3. If a pound of water and a pound of iron expose the same surface area to the direct rays of the sun, which will show the greater change of temperature in an hour?

4. If equal quantities of heat are applied to equal masses of iron and copper, which will show the greater change of temperature?

5. Which would be the more efficient foot warmer, a rubber bag containing 5 lb. of water at 80° C., or a 5-lb. block of iron also at 80° C.? Give reasons.

6. If a number of balls of the same mass but of different materials are heated in boiling water and are then placed on a cake of wax, will they all melt the same quantity of wax? Why?

7. How many calories of heat will it take to raise the temperature of 50 gm. of water from 10° C. to 70° C.? If this heat were all applied to 1 liter of water at 20° C., to what temperature would it raise the water?

8. If 90 gm. of mercury at 100° C. are stirred with 100 gm. of water at 20° C. and the resulting temperature is 22.3° C., what is the specific heat of mercury?

9. If the specific heat of iron is 0.112, how much heat will be required to raise the temperature of 2.5 kgm. of iron from 15° C. to 100° C.?

10. A copper ball weighing 5 kgm. is heated to a temperature of 100° C., and when placed in water raises its temperature from 20° C. to 25° C. How many grams of water are there, the specific heat of copper being 0.095?

V. CHANGE OF STATE

321. The Melting Point.—A body is said to *melt* or *fuse* when it changes from the solid to the liquid state by the application of heat. The change is called *melting*, *fusion*, or *liquefaction*. The temperature at which fusion takes place is called the *melting point*. Solidification or freezing is the converse of fusion, and the temperature of solidification is usually the same as the melting point of the same substance. Water, if undisturbed, may be cooled a number of degrees below 0° C., but if it is disturbed it usually freezes at once, and its temperature rises to the freezing point.

The melting point of crystalline bodies is well marked. A mixture of ice and water will remain without change if the temperature of the room is 0° C.; but if the temperature is above zero, some of the ice will melt; if it is below zero, some of the water will freeze. Some substances, like wax, glass, and wrought iron, have no sharply defined melting point. They first soften and then pass more or less slowly into the condition of a viscous liquid. It is this property which permits of the bending and molding of glass, and the welding and forging of iron.

322. Change in Volume accompanying Fusion.—Fit to a small bottle a perforated stopper through which passes a fine glass tube. Fill with water recently boiled to expel the air, the water extending halfway up the tube. Pack the apparatus in a mixture of salt and finely broken ice. The water column at first will fall slowly, but in a few minutes it will begin to rise, and will continue to do so until water flows out of the top of the tube. The water in the bottle freezes, expands, and causes the overflow.

Most substances occupy a larger volume in the liquid state than in the solid; that is, they expand in liquefying.

A few substances, like water and bismuth, expand in solidifying. When water freezes, its volume increases 9 per cent. If this expansion is resisted, water in freezing is capable of exerting a force of about 2000 kgm. per square centimeter.

323. Effect of Pressure on the Melting Point.—Support a rectangular block or prism of ice on a stout bar of wood. Pass a thin iron wire around the ice and the bar of wood, and suspend on it a weight of about 25 lb. The pressure of the wire lowers the melting point of the ice immediately under it and the ice melts; the water, after passing around the wire, where it is relieved of pressure, again freezes. In this way the wire passes slowly through the ice, leaving the block solidly frozen.

A rough numerical statement of the effect of pressure on the freezing point of water is that a pressure of one ton per square inch lowers the freezing point to $-1°$ C. Familiar examples of refreezing, or *regelation*, are the hardening of snowballs under the pressure of the hands, the formation of solid ice in a roadway where it is compressed by vehicles and the hoofs of horses, and frozen footforms in compact ice after the loose snow has melted around them. The ice of a glacier melts where it is under the enormous pressure of the descending masses above it. The melting permits the ice to accommodate itself to abrupt changes in the rocky channel, and a slow iceflow results. As soon as the pressure at any surface is relieved, the water again freezes. Pressure lowers melting point

324. Heat of Fusion.—When a solid melts, a quantity of heat disappears; and, conversely, when a liquid solidifies, the amount of heat generated is the same as disappears during liquefaction. The *heat of fusion* of a substance is the number of calories required to melt a

gram of it without change of temperature. The heat of fusion of ice is 80 calories.

As an illustration of the heat of fusion, place 200 gm. of clean ice, broken into small pieces, into 500 gm. of water at 60° C. When the ice has melted, the temperature will be about 20° C. The heat lost by the 500 gm. of water equals $500 \times (60 - 20) = 20{,}000$ calories. This heat goes to melt the ice and to raise the water from it from 0° C. to 20° C. The latter is $200 \times 20 = 4000$ calories. The remainder, $20{,}000 - 4000 = 16{,}000$ calories, went to melt the ice. Then the heat of fusion of ice is $16{,}000 \div 200 = 80$ calories per gram.

325. Heat lost in Solution. — Fill a glass beaker partly full of water at the temperature of the room, and add some ammonium nitrate crystals. The temperature of the water will fall as the crystals dissolve.

This experiment illustrates the fact that heat disappears when a body passes from the solid to the liquid state by solution. The use of salt in soup or of sugar in tea absorbs heat. The heat energy is used to pull down the solid structure.

326. Freezing Mixtures. — Freezing mixtures are based on the absorption of heat necessary to give fluidity. Salt water freezes at a lower temperature than fresh water. When salt and snow or pounded ice are mixed together, both become fluid and absorb heat in the passage from the one state to the other. By this mixture a temperature of −22° C. may be obtained. Still lower temperatures may be reached with other mixtures, notably with sulphocyanide of sodium and water.

327. Vaporization. — Pour a few drops of ether into a beaker and cover loosely with a plate of glass. After a few seconds bring a lighted taper to the mouth of the beaker. A sudden flash will show that the vapor of ether was mixed with the air.

Support on an iron stand a Florence flask two thirds full of water

and apply heat. In a short time bubbles of steam will form at the bottom of the flask, rise through the water, and burst at the top, producing violent agitation throughout the mass.

Vaporization is the conversion of a substance into the gaseous form. If the change takes place slowly from the surface of a liquid, it is called *evaporation;* but if the liquid is visibly agitated by rapid internal evaporation, the process is called *ebullition* or *boiling.*

328. Sublimation. — When a substance passes directly from the solid to the gaseous form without passing through the intermediate state of a liquid, it is said to *sublime.* Arsenic, camphor, and iodine sublime at atmospheric pressure, but if the pressure be sufficiently increased, they may be fused. Ice also evaporates slowly even at a temperature below freezing. Frozen clothes dry in the air in freezing weather. At a pressure less than 4.6 mm. of mercury, ice is converted into vapor by heat without melting.

329. The Spheroidal State. — When a small quantity of liquid is placed on hot metal, as water on a red-hot stove, it assumes a globular or spheroidal form, and evaporates at a rate between ordinary evaporation and boiling. It is then in the *spheroidal state.* The vapor acts like a cushion and prevents actual contact between the liquid and the metal. The globular form is due to surface tension. Liquid oxygen at $-180°$ C. assumes the spheroidal form on water. The temperature of the water is relatively high compared with that of the liquid oxygen.

330. Cold by Evaporation. — Tie a piece of fine linen around the bulb of a thermometer and pour on it a few drops of sulphuric ether. The temperature will at once begin to fall, showing that the bulb has been cooled.

In the evaporation of ether, some of the heat of the thermometer is used to do work on the liquid. The rapid evaporation of liquid ammonia is utilized in making artificial ice. Large tanks of salt brine are cooled by coils of pipe containing liquid ammonia. A pump lowers the pressure in these coils and the ammonia evaporates rapidly with the production of a low temperature. Cans of water set in these tanks are frozen. The ammonia gas is afterwards reduced again to the liquid form by pressure and cooling.

Sprinkling the floor of a room cools the air, because of the heat expended in evaporating the water. Porous water vessels keep the water cool by the evaporation of the water from the outside surface. Liquid carbon dioxide is readily frozen by its own rapid evaporation. Dewar liquefied oxygen by means of the temperature obtained through the successive evaporation of liquid nitrous oxide and ethylene. Similarly, by the evaporation of liquid air he has liquefied hydrogen. The evaporation of liquid hydrogen under reduced pressure has enabled him to obtain a temperature but little removed from the absolute zero, $-273°$ C.

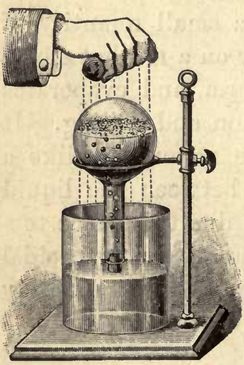


Fig. 278

331. Effect of Pressure on the Boiling Point. — Place a flask of warm water under the receiver of an air pump. It will boil violently when the receiver is exhausted.

Fill a round-bottomed Florence flask half full of water and heat till it boils vigorously. Cork the flask, invert, and support it on a ring stand (Fig. 278). The boiling ceases, but is renewed by applying cold water to the flask. The cold water condenses the vapor, and reduces the pressure within the flask so that the boiling begins again.

The effect of pressure on the boiling point is seen in the low temperature of boiling water at high elevations, and in the high temperature of the water under pressure in digesters used for extracting gelatine from bones. The boiling point of water falls 1° C. for an increase in elevation of about 295 m. At Quito the boiling point is near 90° C.

332. Heat of Vaporization. — The *heat of vaporization* is the number of calories required to change one gram of a liquid at its boiling point into vapor at the same temperature. Water has the greatest heat of vaporization of all liquids. The most carefully conducted experiments show that the heat of vaporization of water under a pressure of one atmosphere is 536.6 calories per gram.

Set up apparatus like that shown in Fig. 279. The steam from the boiling water is conveyed into a beaker containing a known quantity of water at a known temperature. The increase in the mass of the water gives the amount of steam condensed. The "trap" in the delivery tube catches the water that condenses before it reaches the beaker. Suppose that the experiment gave the following data: Amount of water in the beaker, 400 gm. at the beginning, 414.1 gm. at the end, including the thermal capacity of the beaker in terms of water; temperature at the beginning, 20° C., and at the end, 41° C.; observed boiling point, 99° C.; there were 14.1 gm. of steam condensed. Now, by the principle that the heat lost or given off by the steam equals that gained by the water, we have

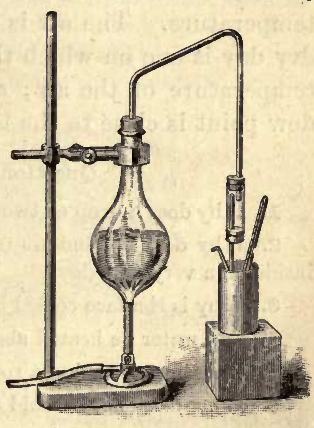


Fig. 279

$$400 \times (41 - 20) = 14.1 \times l + 14.1 \times (99 - 41);$$

whence $l = 537.7$ cal. per gram.

333. The Dew Point. — *The dew point is the temperature at which the aqueous vapor of the atmosphere begins to condense.* If water at the temperature of the room be poured into a polished nickel-plated beaker and some small pieces of ice be added with stirring, a mist will soon collect on the outside of the vessel. The temperature of the water is then the dew point. The formation of clouds, the precipitation of dew, and the "sweating" of pitchers containing ice water are evidence of the existence of water vapor in the atmosphere. Dew collects on objects when their temperature drops below the dew point.

The amount of moisture that the air can contain depends on the temperature. The terms *dryness* and *moistness*, applied to the air, are purely relative. They indicate the proportion of water vapor actually present in comparison with what the air could hold when saturated at the same temperature. The air is saturated at the dew point. A dry day is one on which the dew point is much below the temperature of the air; a damp day is one on which the dew point is close to the temperature of the air.

Questions and Problems

1. Why does a drop or two of alcohol feel cold on the hand?

2. Why do the windows of an occupied house frost over on the inside on a very cold day?

3. Why is the face cooled by fanning?

4. Can water be heated above 100° C.? How?

5. Why does warming a room make it drier?

6. Why does one feel cold when sitting in a draft?

7. Why is water better than any other liquid for heating purposes?

8. Why is there no dew on windy nights?

9. Why will pressure cause two blocks of ice to adhere? Will they adhere if their temperature is much below freezing?

10. How much heat does it take to melt 100 gm. of ice?

11. How much heat does it take to convert 100 gm. of water at 100° C. into steam at 100° C.?

12. How much heat will it take to convert 75 gm. of ice into steam?

13. 50 gm. of ice at 0° C. are put into 50 gm. of water at 40° C. How much of the ice will melt?

14. How much ice must be put into 100 gm. of water at 60° C. to lower the temperature to 20° C.?

15. If 25 gm. of steam at 100° C. are condensed in 20 gm. of water at 15° C., what will be the resulting temperature?

16. How much ice can be melted by 50 gm. of steam at 100° C. if none of the heat is lost?

VI. TRANSMISSION OF HEAT

334. Conduction. — Twist together two stout wires, iron and copper, of the same diameter, forming a fork with long parallel prongs and a short stem. Support them on a wire stand (Fig. 280), and heat the twisted ends. After several minutes find the point on each wire,

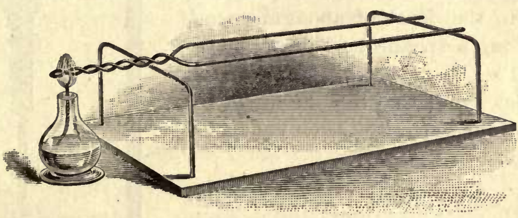


Fig. 280

farthest from the flame, where a sulphur match ignites when held against the wire. This point will be found farther along on the copper than on the iron, showing that the former has led the heat farther from its source.

Prepare a cylinder of uniform diameter, half of which is made of brass and half of wood. Hold a piece of writing paper firmly around

the junction like a loop (Fig. 281). By applying a Bunsen flame the paper in contact with the wood is soon scorched, while the part in contact with the brass is scarcely injured. The metal conducts the heat away and keeps the temperature of the paper below the point of ignition. The wood is a poor conductor.

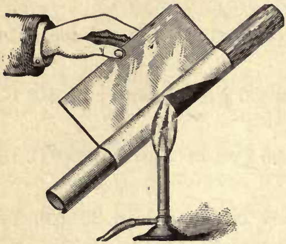


Fig. 281

These experiments show that solids differ in their conductivity for heat. The metals are the best conductors; wood, leather, flannel, and organic substances in general are poor conductors; so also are all bodies in a powdered state, owing doubtless to a lack of continuity in the material.

335. Conductivity of Liquids. — Pass a glass tube surmounted with a bulb through a cork fitted to the neck of a large funnel. Support the apparatus as shown in Fig. 282. The glass stem should stand in colored water. Heat the bulb slightly to expel some air, so that the liquid will rise in the tube. Fill the funnel with water, covering the bulb to the depth of about one centimeter. Pour a spoonful of ether on the water and set it on fire. The steadiness of the index shows that little if any of the heat due to the burning ether is conducted to the bulb.

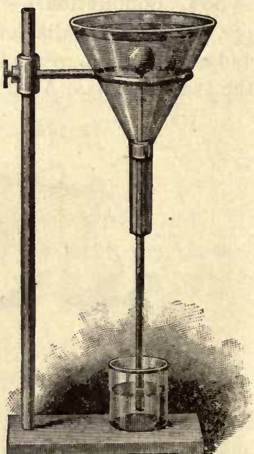


Fig. 282

This experiment shows that water is a poor conductor of heat. This is equally true of all liquids except molten metals.

336. Conductivity of Gases. — The conductivity of gases is very small, and its determination is very difficult because of radiation and convection. The conductivity of hydrogen is

about 7.1 times that of air, while the conductivity of water is 25 times as great.

337. Applications of Conductivity. — If we touch a piece of marble or iron in a room, it feels cold, while cloth and wood feel distinctly warmer. The explanation is that the articles which feel cold are good conductors of heat and carry it away from the hand, while the poor conductors do not.

The good heat-conducting property of copper or brass is turned to practical account in the Davy miner's lamp. The flame is completely inclosed in metal and fine wire gauze. The gauze by conducting away heat keeps any fire damp outside the lamp below the temperature of ignition and so prevents explosions. The action of the gauze is readily illustrated by holding it over the flame of a Bunsen burner (Fig. 283). The flame does not pass through unless the gauze is heated to redness. If the gas is first allowed to stream through the gauze, it may be lighted on top without being ignited below.

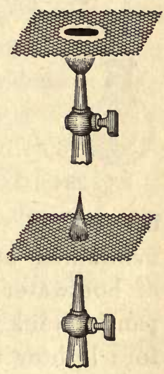


Fig. 283

The handles on metal instruments that are to be heated are usually made of some poor conductor, as wood, bone, etc.; or else they are insulated by the insertion of some non-conductor, as in the case of the handles to silver teapots, where pieces of ivory are inserted to keep them from becoming too hot.

The non-conducting character of air is utilized in houses with hollow walls, in double doors and double windows, and in clothing of loose texture. The warmth of woolen articles and of fur is due mainly to the fact that much

air is inclosed within them on account of their loose structure.

338. Convection. — Set up apparatus as shown in Fig. 284, and support it on a heavy iron stand. Fill the flask and connecting tubes with water up to a point a little above the open end of the vertical tube at C. Apply a Bunsen flame to the flask B. A circulation of water is set up in the apparatus, as shown by the arrows. The circulation is made visible by coloring the water in the reservoir blue and that in the flask red.

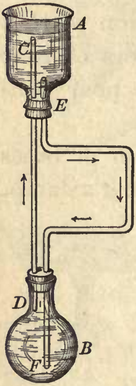


Fig. 284

The process of conveying heat by the transference of the heated matter itself is known as *convection*. Currents set up in this manner are called *convection currents*. The heating of buildings by hot water conveyed though a pipe to an expansion tank at the top of the building and back through radiators in the rooms is an application of convection. The circulation is mantained because the column of hot water leading to the expansion tank is hotter and therefore lighter then the water in the return pipes.

339. Convection in Gases. — Set a short piece of lighted candle in a shallow beaker and place over it a lamp chimney. Pour into the beaker enough water to close the lower end of the chimney. Place in the top of the chimney a T-shaped piece of tin as a short partition (Fig. 285). If a piece of smoldering paper be held over one edge of the chimney, the smoke will pass down one side of the partition and up the other. If the partition be removed, the flame will usually go out.

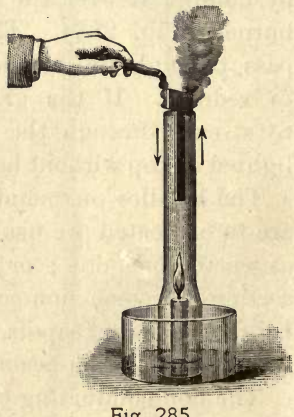


Fig. 285

Convection currents are more easily set up in gases than in liquids. They are utilized in heating buildings by a hot-air furnace. Convection currents of air on a large scale are present near the seacoast. The wind is a sea breeze during the day, because the air moves in from the cooler ocean to take the place of the air rising over the heated land. As soon as the sun sets, the ground cools rapidly by radiation, and the air over it is cooler than over the sea. Hence the reversal in the direction of the wind, which is now a land breeze.

340. Radiation. — When one stands near a hot stove, one is warmed neither by heat conducted nor conveyed by the air. The heat energy of a hot body is constantly passing into space as *radiant energy* in the ether. Radiant energy becomes heat again only when it is absorbed by bodies upon which it falls. Energy transmitted in this way is, for convenience, referred to as *radiant heat*, although it is transmitted as radiant energy, and is transformed into heat only by absorption. Radiant heat and light are physically identical, but are perceived through different avenues of sensation. Radiations that produce sight when received though the eye give a sensation of warmth through the nerves of touch, or heat a thermometer when incident upon it. The long ether waves do not affect the eye, but they heat a body which absorbs them.

341. Laws of Heat Radiation. — The following laws have been established experimentally: —

I. *Radiation proceeds in straight lines.* This law is illustrated in the use of fire screens and sunshades, and by the drop in temperature when the sun is obscured by dense clouds.

II. *The amount of radiant energy received by a body*

from any small area varies inversely as the square of its distance from this area as a source. This law is the same as the one relating to the intensity of illumination in light.

III. *Radiant energy is reflected from a polished surface so that the angles of incidence and reflection are equal.* An interesting application is the Ericsson solar engine. The radiant energy of the sun is concentrated by large concave reflectors on metal pipes filled with water. The heat is great enough to generate steam to operate a small steam engine.

IV. *The capacity of a surface to reflect radiant energy depends both on the polish of the surface and the nature of the material.* Polished brass is one of the best reflectors, and lampblack is the poorest.

V. *The rate at which the temperature of a cooling body falls by radiation is proportional to the excess of its temperature over that of the surrounding medium.* This is known as Newton's *Law of Cooling;* it holds approximately for small differences of temperature but fails when the excess is large. According to this law a body at a temperature of 30° C. cools twice as fast as one of 25° C. in air at 20° C., for the excess 10°, in the first case, is twice 5°, the excess in the second.

VI. *The transmission of radiant heat through various substances depends on the wave length of the radiations, and the thickness and character of the substance itself.* Those transmitting a large part of the heat energy, as rock salt, are said to be *diathermanous:* those absorbing a large part, as water and alum, are *athermanous.* Glass is diathermanous to radiations from a source of high temperature,

but athermanous to radiations from sources of low temperature. The radiant energy from the sun passes readily through the atmosphere of the earth, warming its surface; but the radiations from the earth are stopped to a large extent by the enveloping atmosphere.

Questions and Problems

1. Why does water cool faster in a pan than in a pitcher?

2. Why does sawdust keep ice from melting?

3. Why does snow protect the ground from freezing?

4. Why does the "thermos" bottle keep its contents hot for such a long time?

5. Why is glass used for the roofs of greenhouses?

6. What principles of heat are applied in the construction of a "fireless cooker"?

7. Why are steam pipes in the basement of a building covered with asbestos, felt, or magnesia?

8. Should the surface of a steam or water radiator be polished or rough?

9. Why are the extremes of island climates less than elsewhere?

10. In heating water why should the heat be applied at the bottom of the vessel rather than at the top?

11. What will be the effect on the reading of a thermometer to cover the bulb with a wet cloth?

12. In what way does a grate fire heat a room?

13. A thick glass tumbler cracks when hot water is poured into it. Why does not a thin glass beaker crack under the same circumstances?

14. Why are clouds a protection against frost?

15. Why is the boiling point of water in the boiler of a steam engine above 100° C?

16. Why will a moistened finger or the tongue freeze very quickly to a piece of very cold iron, but not to a piece of wood?

VII. HEAT AND WORK

342. Heat from Mechanical Action. — Strike the edge of a piece of flint a glancing blow with a piece of hardened steel. Sparks will fly at each blow.

Pound a bar of lead vigorously with a hammer. The temperature of the bar will rise.

In the cavity at the end of a piston of a fire syringe place a small piece of tinder, such as is employed in cigar lighters (Fig. 286). Force the piston quickly into the barrel. If the piston is immediately withdrawn the tinder will probably be on fire.

These experiments show that mechanical energy may be transformed into heat. Some of the energy of the descending flint, the hammer, and the piston has in each case been transferred to the molecules of the bodies themselves, increasing their kinetic energy, that is, raising their temperature.


Fig. 286

Savages kindle fire by rapidly twirling a dry stick, one end of which rests in a notch cut in a second dry piece. The axles of carriages and the bearings in machinery are heated to a high temperature when not properly lubricated. The heating of drills and bits in boring, the heating of saws in cutting timber, the burning of the hands by a rope slipping rapidly through them, the stream of sparks flying from an emery wheel, are instances of the same kind of transformation; the work done against friction produces kinetic energy in the form of heat.

343. The Mechanical Equivalent of Heat. — In 1840 Joule of Manchester in England began a series of experiments to determine the numerical relation between the unit of heat and the foot pound. His experiments extended over a period of forty years. His most successful method

James Watt (1736–1819) was born at Greenock, Scotland, and was educated as an instrument maker. In studying the defects of the steam engines then in use, he was led to make many very important improvements, culminating in his invention of the double-acting steam engine. He invented the ball governor, the cylinder jacket, the D-valve, the jointed parallelogram for securing rectilinear motion to the piston, the mercury steam-gauge, and the water-gauge. He is also to be credited with the first compound engine, a type of engine extensively used to-day.

James Prescott Joule (1818–1889), the son of a Manchester brewer, was born at Salford, England. He became known to the scientific world through his contributions in heat, electricity, and magnetism. His greatest achievement was establishing the modern kinetic theory of heat by determining the mechanical equivalent of heat. His experiments on this subject were continued through a period of forty years. In recognition of his great work he was presented with the Royal Medal of the Royal Society of England in 1852.

consisted in measuring the heat produced when a measured amount of work was expended in heating water by stirring it with paddles driven by weights falling through a known height. His final result was that 772 ft.-lb. of work, when converted into heat, raise the temperature of 1 lb. of water 1° F., or 1390 ft.-lb. for 1° C. The later and more elaborate researches of Rowland in 1879 and of Griffiths in 1893 show that the relation is 778 ft.-lb. for 1° F., or 427.5 kgm.-m. for 1° C.; that is, if the work done in lifting 427.5 kgm. one meter high is all converted into heat, it will raise the temperature of 1 kgm. of water 1° C. This relation is known as *the mechanical equivalent of heat.* Its value expressed in absolute units is 4.19×10^7 ergs per calorie.

344. The Steam Engine. — The most important devices for the conversion of heat into mechanical work are the steam engine and the gas engine. The former in its essential features was invented by James Watt. In the reciprocating steam engine a piston is moved alternately in opposite directions by the pressure of steam applied first to one of its faces and then to the other. This reciprocating or to-and-fro motion is converted into rotatory motion by the device of a connecting rod, a crank, and a flywheel.

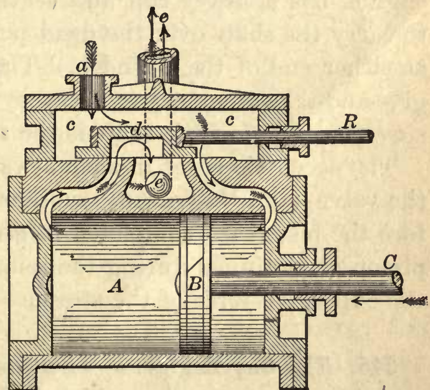


Fig. 287

In Fig. 287 are shown in section the cylinder, piston,

and slide valve of a simple steam engine. The piston B is moved in the cylinder A by the pressure of the steam admitted through the inlet pipe a. The slide valve d works in the steam chest cc and admits steam alternately to the two ends of the cylinder through the steam ports at either end.

When the valve is in the position shown, steam passes into the right-hand end of the cylinder and drives the piston toward the left. At the same time the other end is connected with the exhaust pipe ee through which the steam escapes, either into the air, as in a *high-pressure non-condensing engine*, or into a large condensing chamber, as in a *low-pressure condensing engine*.

The slide valve d is moved by the rod R, connected to an eccentric, which is a round disk mounted a little to one side of its center, on the engine shaft. It has the effect of a crank. The flywheel, also mounted on the shaft of the engine, has a heavy rim and serves as a store of energy to carry the shaft over the dead points when the piston is at either end of the cylinder. There is in the flywheel a give-and-take of energy twice every revolution, and a fairly steady rotation of the shaft is the result.

The eccentric is set in such a way that the rod R closes the valve admitting steam to either end of the cylinder before the piston has completed its stroke; the motion of the piston is continued during the remainder of the stroke by the expansive force of the steam.

345. The Gas Engine. — The *gas engine* is a type of *internal combustion engine*, which includes motors using gas, gasoline, kerosene, or alcohol as fuel. The fuel is introduced into the cylinder of the engine, either as a gas or a vapor, mixed with the proper quantity of air to produce a

good explosive mixture. The mixture is ignited at the right instant by means of an electric spark. The explosion and the expansive force of the hot gases drive the piston forward in the cylinder.

In the *four-cycle* type of gas engine, the explosive mixture is drawn in and ignited in each cylinder only every other revolution of the engine, while in the *two-cycle* type an explosion occurs every revolution. The former type is used in most motor car engines, and the latter in small motor boats.

The operation of a four-cycle engine is illustrated in 1, 2, 3, and 4 of Fig. 288, which shows the four steps in a complete cycle. The inlet valve *a* and the exhaust valve *b* are operated by the cams *c* and *d*. Both valves are kept normally closed by springs surrounding the valve stems. The small shafts to which the two cams are fixed are driven by the spur wheel *e* on the shaft of the engine. This wheel engages with the two larger spur wheels on the cam shafts, each having twice as many teeth as *e* and forming with it a two-to-one gear, so that *c* and *d* rotate once in every two revolutions of the crank shaft. The piston *m* has packing rings; *h* is the connecting rod, *k* the crank shaft, and *l* the spark plug.

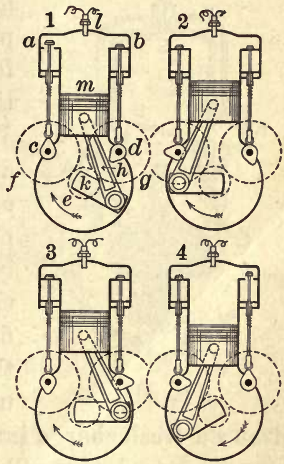


Fig. 288

In diagram 1 the piston is descending and draws in the charge through the open valve *a*; in 2 both valves are closed and the piston compresses the explosive charge;

about the time the piston reaches its highest point, the charge is ignited by a spark at the spark plug, and the working stroke then takes place, as in 3, both valves remaining closed; in 4 the exhaust valve *b* is opened by the cam *d*, and the products of the combustion escape through the muffler, or directly into the open air. The piston has now traversed the cylinder *four times*, twice in each direction, and the series of operations begins again.

Fig. 289 is a section of a two-cycle engine. During the up-stroke of the piston *P* a charge is drawn through *A* into the crank case *C*. At the same time a charge in the cylinder is compressed and is ignited by a spark when the compression is greatest. The piston is forced down, and when it passes the port *E* the exhaust takes place. When the admit port *I* is passed, a charge enters from the crank case. To prevent this charge from passing across and escaping at *E*, it is made to strike against a projection *B* on the piston, which deflects it upward. The momentum of the balance wheel carries the piston upward, compresses the charge, and draws a fresh charge into the crank case. The piston has now traversed the cylinder *twice*, once in each direction, and the same series of operations is again repeated.

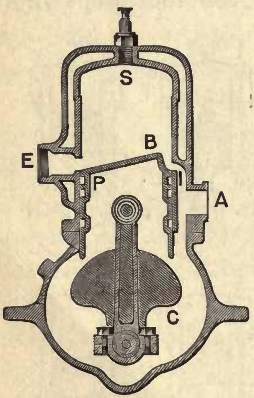


Fig. 289

346. The Aeroplane. — If a large flat surface, placed obliquely to the ground, be moved along somewhat rapidly, it will be lifted upward by the vertical component of the reaction of the air against it, just as a kite is lifted (§ 108).

This is the principle applied in the aeroplane. In this device, whether monoplane or biplane, large bent surfaces attached to a stout light frame are driven through the air by rapidly rotating propellers operated by a powerful gasoline engine, just as a steamboat is driven through the water. By means of suitable levers under control of the driver, these planes, or certain auxiliary planes, can be set at an angle to the stream of air against which they are propelled. Then, as in the kite, they rise through the air

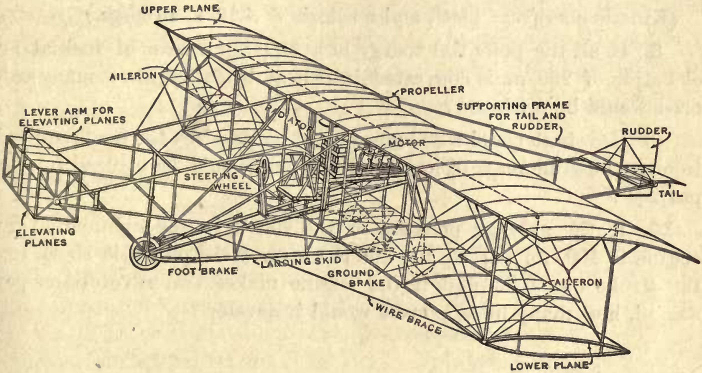


Fig. 290

by the action of the vertical component of the force of the air against their under surfaces. Vertical planes are attached to the same frame to serve as rudders in steering either to the right or the left; movements either up or down are regulated by the inclination of the auxiliary or elevating planes as already stated. Fig. 290 illustrates one of the many types of aeroplanes now in use.

Questions and Problems

1. Why does the temperature of the air under the bell jar of an air pump fall when the pump is worked?

2. Is there a difference in the temperature of the steam as it enters a steam engine and as it leaves at the exhaust? Explain.

3. Lead bullets are sometimes melted when they strike a target. Explain.

4. Does warm clothing keep the cold out? What does it do?

5. Describe the movements of the air in a room heated by a stove.

6. Is there any less moisture in the air after it has passed through a heated furnace into a room than there was before?

7. A mass of 200 gm. moving with a velocity of 50 m. per second, is suddenly stopped. If all its energy is converted into heat, how many calories would it be?

(Kinetic energy $= \frac{1}{2} mv^2$, and a calorie $= 4.19 \times 10^7$ ergs.)

8. If all the potential energy of a 300 kgm. mass of rock at an elevation of 250 m. is converted into heat by falling, how many calories would be produced?

9. How high could a 200 gm. weight be lifted by the heat required to melt the same mass of ice, if all the heat could be utilized for the purpose?

10. If the average pressure of the steam in the cylinder of an engine is 100 lb. per sq. in., and the area of the piston is 80 sq. in., the stroke one foot, and if the engine makes two revolutions per second, how many horse powers would it develop?

CHAPTER X

MAGNETISM

I. MAGNETS AND MAGNETIC ACTION

347. Natural Magnets. — Black oxide of iron, commonly called magnetite, is widely distributed and is sometimes found to possess the property of attracting small pieces of iron. At a very early date such pieces of iron ore were found near Magnesia in Asia Minor, and they were therefore called *magnetic stones* and later *magnets*. They are now known as *natural magnets*, and the properties peculiar to them as *magnetic properties*.

Dip a piece of natural magnet into iron filings; they will adhere to it in tufts, not uniformly over its surface, but chiefly at the ends and on projecting edges (Fig. 291).

Suspend a piece of natural magnet by a piece of untwisted thread (Fig. 292). Note its position, then disturb it slightly, and again let it come to rest. It will be found that it invariably returns to the same position, the line connecting the two ends to which the filings chiefly adhered in the preceding experiment lying north and south.

Fig. 291

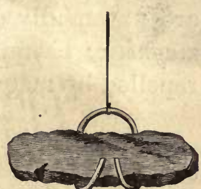


Fig. 292

This directional property of the natural magnet was early turned to account in navigation, and secured for it the name of *lodestone* (leading-stone).

348. Artificial Magnets. — Stroke the blade of a pocket knife from end to end, and always in the same direction, with one end of a

lodestone. Touch it to iron filings; they will cling to its point as they did to the lodestone. The knife blade has become a magnet.

Use the knife blade of the last experiment to stroke another blade. This second blade will also acquire magnetic properties, and the first one has suffered no loss.

Artificial magnets, or simply magnets, are bars of hardened steel that have been made magnetic by the application of some other magnet or magnetizing force. The form of artificial magnets most commonly met with are the *bar* and the *horseshoe* (Fig. 293).

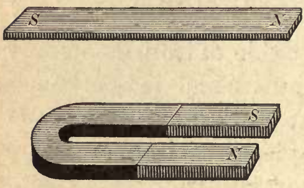


Fig. 293

349. Magnetic Substances. — Any substance that is attracted by a magnet or that can be magnetized is a *magnetic substance.* Faraday showed that most substances are influenced by magnetism, but not all in the same way nor to the same degree. Iron, nickel, cobalt, and manganese are powerfully attracted by magnets and are said to be *magnetic;* bismuth, antimony, and zinc act as if they are repelled by magnets and they are called *diamagnetic.*

350. Polarity. — Roll a bar magnet in iron filings. It will become thickly covered with the filings near its ends. Few, if any, will adhere at the middle (Fig. 294).

Fig. 294

The experiment shows that the greater part of the magnetic attraction is concentrated at or near the ends of the magnet. They are called its *poles*, and the magnet is said to have *polarity.* The line joining the poles of a long slender magnet is its *magnetic axis.*

Michael Faraday, 1791–1867, was born near London, England. He was the son of a blacksmith and received but little schooling, being apprenticed to a bookbinder when only thirteen years of age. While employed in the bindery he became interested in reading such scientific books as he found there. Later he applied to Sir Humphry Davy for consideration and was made Davy's assistant. From this time his rise was rapid; in 1816 he published his first scientific memoir; in 1824 he became a member of the Royal Society; in 1825 he was elected director of the Royal Institution; in 1831 he announced the discovery of magneto-electric induction, the most important scientific discovery of any age. In 1833 he was elected professor of chemistry in the Royal Institution. He was a remarkable experimenter and a most interesting lecturer, and amid all his wonderful achievements, he was utterly wanting in vanity.

351. North and South Poles. — Straighten a piece of watch spring 8 or 10 cm. long, stroke it from end to end with a magnet, and float it on cork in a vessel of water (Fig. 295). It will turn from any other position to a north and south one, and invariably with the same end north.

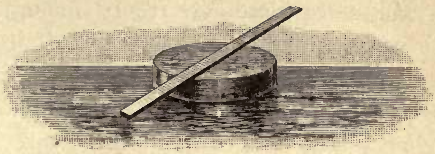


Fig. 295

The end of a magnet pointing toward the north is called the *north-seeking pole*, and the other the *south-seeking pole*. They are commonly called simply the *north pole* and the *south pole*.

352. Magnetic Needle. — A slender magnetized bar, suspended by an untwisted fiber or pivoted on a point so as to have freedom of motion about a vertical axis is a *magnetic needle* (Fig. 296). The direction in which it comes to rest without torsion or friction is called the *magnetic meridian*.

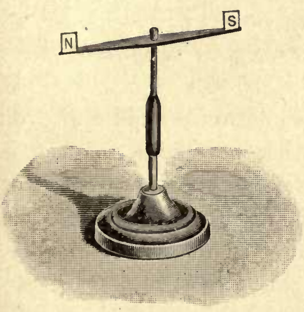


Fig. 296

Fasten a fiber of unspun silk to a piece of magnetized watch spring about 2 cm. long so that it will hang horizontally. Suspend it inside a wide-mouthed bottle by attaching the fiber to a cork fitting the mouth of the bottle. The little magnetic needle will then be protected from currents of air. It may be made visible at a distance by sticking fast to it a piece of thin white paper.

353. Magnetic Transparency. — Cover the pole of a strong bar magnet with a thin plate of glass. Bring the face of the plate opposite the pole in contact with a pile of iron tacks. A number will be found to adhere, showing that the attraction takes place through glass. In like manner, try thin plates of mica, wood, paper, zinc,

copper, and iron. No perceptible difference will be seen except in the case of the iron, where the number of tacks lifted will be much less.

Magnetic force acts freely through all substances except those classified as *magnetic*. Soft iron serves as a more or less perfect screen to magnetism. Watches may be protected from magnetic force that is not too strong by means of an inside case of soft sheet iron.

354. First Law of Magnetic Action. — Magnetize a piece of large knitting-needle, about four inches long, by stroking it from the middle to one end with the north pole of a bar magnet, and then from the middle to the other end with the south pole. Repeat the operation several times. Present the north pole of the magnetized knitting-needle to the north pole of the needle suspended in the bottle. The latter will be repelled. Present the same pole to the south pole of the little magnetic needle; it will be attracted. Repeat with the south pole of the knitting-needle and note the deflections.

The results may be expressed by the following law of magnetic attraction and repulsion: —

Like magnetic poles repel and unlike magnetic poles attract each other.

355. Testing for Polarity.—The magnetic needle affords a ready means of ascertaining which pole of a magnet is the north pole, for the north pole of the magnet is the one that repels the north pole of the magnetic needle. Repulsion is the only sure test of polarity for reasons that will appear in the experiments that follow.

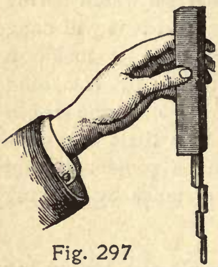


Fig. 297

356. Induced Magnetism. — Hold vertically a strong bar magnet and bring up against its lower end a short cylinder of soft iron. It will adhere. To the lower end of this one attach another, and so on in a series of as many as will stick (Fig. 297). Carefully detach the magnet from the first piece of iron and withdraw it slowly. The pieces of iron will all fall apart.

The small bars of iron hold together because they become temporary magnets. Magnetism produced in magnetic substances by the influence of a magnet near by or in contact with them is said to be *induced*, and the action is called *magnetic induction.* Magnetic induction precedes attraction.

357. Unlike Polarity Induced. — Place a bar magnet in line with the magnetic axis of a magnetic needle, with its north pole as near as possible to the north pole of the needle without appreciably repelling it (Fig. 298). Insert a bar of soft iron between the magnet and the needle. The north pole of the needle will be immediately repelled.

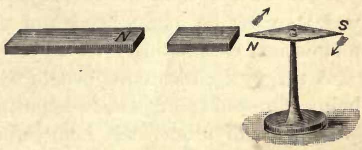


Fig. 298

The repulsion of the north pole of the needle by the end of the soft iron bar next to it shows that this end of the bar has acquired a polarity the same as that of the magnet, that is, north polarity. Then the other end adjacent to the magnet must have acquired the opposite polarity.

When a magnet is brought near a piece of iron, the iron is magnetized by induction, and there is attraction because the adjacent poles are unlike. When a bunch of iron filings or tacks adhere to a magnet, each filing or tack becomes a magnet and acts inductively on the others and all become magnets. Weak magnets may have their polarity reversed by the inductive action of a strong magnet.

358. Permanent and Temporary Magnetism. — When a piece of hardened steel is brought near a magnet, it acquires magnetism as the piece of soft iron does under the same conditions; but the steel retains its magnetism when the magnetizing force is withdrawn, while the soft

iron does not. In the experiment of § 356 the soft iron ceases to be a magnet when removed to a distance from the bar magnet. In addition, therefore, to the *permanent magnetism* exhibited by the magnetized steel, we have *temporary magnetism* induced in a bar of soft iron when it is brought near a magnet or in contact with it.

II. NATURE OF MAGNETISM

359. Magnetism a Molecular Phenomenon. — If a piece of watch spring be magnetized and then heated red hot, it will lose its magnetism completely.

A magnetized knitting-needle will not pick up as many tacks after being vibrated against the edge of a table as it did before.

A piece of moderately heavy and very soft iron wire of the form shown in Fig. 299 can be magnetized by stroking it gently with a bar magnet. If given a sudden twist, it loses at once all the magnetism imparted to it.

Fig. 299

A piece of watch spring attracts iron filings only at its ends. If broken in two in the middle, each half will be a magnet and will attract filings, two new poles having been formed where the original magnet was neutral. If these pieces in turn be broken, their parts will be magnets. If this division into separate magnets be conceived to be carried as far as the molecules, they too would probably be magnets.

It is worthy of notice that magnetization is facilitated by jarring the steel, or by heating it and letting it cool under the influence of a magnetizing force. If an iron bar is rapidly magnetized and demagnetized, its temperature is raised. A steel rod is slightly lengthened by magnetization and a faint click may be heard if the magnetization is sudden.

360. Theory of Magnetism. — The facts of the preceding article indicate that the seat of magnetism is the molecule, that the individual molecules are magnets, that in an un-

magnetized piece of iron the poles of the molecular magnets are turned in various directions, so that they form stable combinations or closed magnetic chains, and hence exhibit no magnetism external to the bar. In a magnetized bar the larger portion of the molecules have their magnetic axes pointing in the same direction, the completeness of the magnetization depending on the completeness with which this uniformity of direction is secured.

III. THE MAGNETIC FIELD

361. Lines of Magnetic Force. — Place a sheet of paper over a small bar magnet and sift iron filings evenly over it from a bottle with a piece of gauze tied over the mouth, tapping the paper gently to aid the filings in arranging themselves under the influence of the magnet. They will cling together in curved lines, which diverge from one pole of the magnet and meet again at the opposite pole.

These lines are called *lines of magnetic force* or of *magnetic induction.* Each particle of iron becomes a magnet by induction; hence *the lines of force are the lines along which magnetic induction takes place.*

362. Magnetic Fields. — *A magnetic field is the space around a magnet in which there are lines of magnetic*

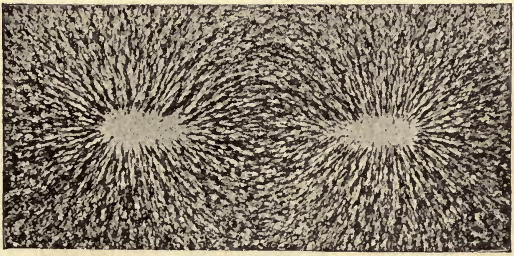


Fig. 300

force. Fig. 300 was made from a photograph of the magnetic field of a bar magnet in a plane passing through the magnetic axis. These

lines of force branch out from the north pole, curve round through the air to the south pole, and complete their circuit through the magnet itself.

Fig. 301 shows the field about two bar magnets placed with their unlike poles adjacent to each other. Many of the lines from the north pole of the one extend across to the south pole of the other, and this connection denotes attraction.

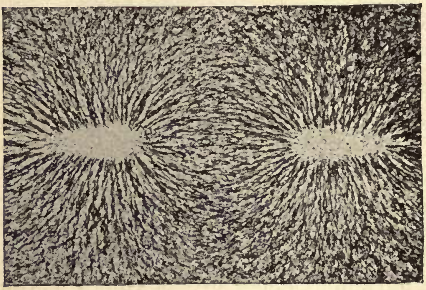


Fig. 301

Fig. 302 shows the field about two bar magnets with their like poles adjacent to each other. None of the lines springing from either pole extend across to the neighboring pole of the other magnet. This is a picture of magnetic repulsion.

363. Properties of Lines of Force. — Lines of magnetic force have the following properties: (*a*) They are under tension, exerting a pull in the direction of their length; (*b*) they spread out as if repelled from one another at right angles to their length; (*c*) they never cross one another; (*d*) they form continuous closed curves.

364. Direction of Lines of Force. — Hold a mounted magnetic needle about 1 cm. long near a bar magnet. It will place itself tangent to the line of force passing through it.

Suspend by a fine thread about 60 cm. long a strongly magnetized sewing needle with its north pole downward. Bring this pole of the needle over the north pole of a horizontal bar magnet (Fig. 303). It will be repelled and will

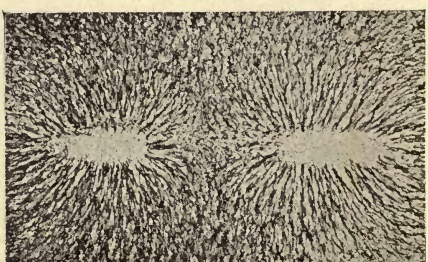


Fig. 302

move along a curved line of force toward the south pole of the magnet.

The direction of a line of force at any point is that of a line drawn tangent to the curve at that point, and the positive direction is that in which a north pole is urged. Since the north pole of a magnetic needle is repelled by the north pole of a bar magnet, an observer standing with his back to the north pole of a magnet looks in the direction of the lines of force coming from that pole.

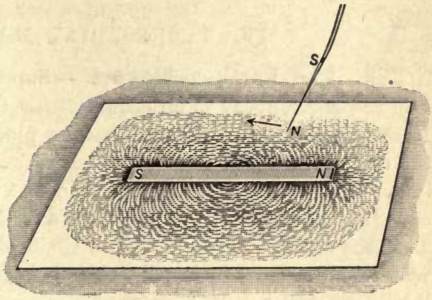


Fig. 303

365. Permeability. — Place a piece of soft iron near the pole of a bar magnet and map out the field with iron filings. The lines are displaced by the iron and are gathered into it (Fig. 304).

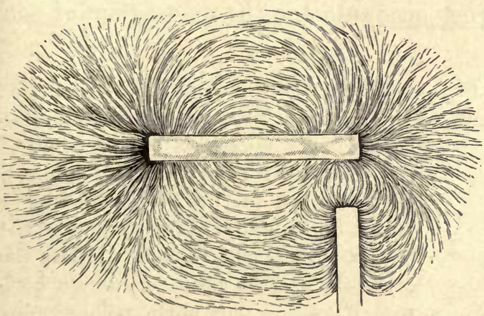


Fig. 304

When iron is placed in a magnetic field, the lines of force are concentrated by it. This property possessed by iron, when placed in a magnetic field, of concentrating the lines of force and increasing their number, is known as *permeability*. The superior permeability of soft iron ex-

plains the action of magnetic screens (§ 353). In the case of the watch shield, the lines of force follow the iron and do not cross it; the watch is thus protected from magnetism because the lines of force do not pass through it.

IV. TERRESTRIAL MAGNETISM

366. The Earth a Magnet. — Support a thoroughly annealed iron rod horizontally in an east-and-west line and test it for polarity. It should show no magnetism. Now place it north and south with the north end about 70° below the horizontal. While in this position, tap it with a hammer and then test it for polarity. The lower end will be found to be a north pole and the upper end a south pole. Turn the rod end for end, hold in the former position, and tap again with a hammer. The lower end will again become a north pole and the magnetism has been reversed.

This experiment shows that the earth acts as a magnet on the iron rod and magnetizes it by induction. Similarly, iron objects, such as a stove, a radiator, vertical steam pipes, iron columns and hitching posts become magnets with the lower end a north pole. The inductive action of the earth as a magnet accounts for the magnetism of natural magnets.

367. Magnetic Dip. — Thrust two unmagnetized knitting needles through a cork at right angles to each other (Fig. 305). Support the apparatus on the edges of two glasses, with the axis in an east-and-west line, and the needle adjusted so as to rest horizontally. Now magnetize the needle, being careful not to displace the cork. It will no longer assume a horizontal position, the north pole dipping down as if it had become heavier.

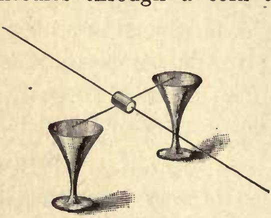


Fig. 305

The *inclination* or *dip* of a needle is the angle its magnetic axis makes with a horizontal plane. A needle mounted so as to turn about

a horizontal axis through its center of gravity is a *dipping needle* (Fig. 306). The dip of the needle at the magnetic poles of the earth is 90°, at the magnetic equator, 0°. In 1907 Amundsen placed the magnetic pole of the northern hemisphere in latitude 75° 5′ N. and longitude 96° 47′ W. The magnetic pole of the southern hemisphere is probably near latitude 73° S. and longitude 150° E.

Isoclinic lines are lines on the earth's surface passing through points of equal dip. They are irregular in direction, though resembling somewhat parallels of latitude.

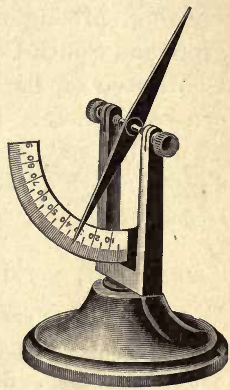


Fig. 306

368. Magnetic Declination. — The magnetic poles of the earth do not coincide with the geographical poles, and consequently the direction of the magnetic needle is not in general that of the geographical meridian. The angle between the direction of the needle and the meridian at any place is the *magnetic declination.* To Columbus belongs the undisputed discovery that the declination is different at different points on the earth's surface. In 1492 he discovered a place of no declination in the Atlantic Ocean north of the Azores. The declination at any place is not constant, but changes as if the magnetic poles oscillate, while the mean position about which they oscillate is subject to a slow change of long period. The annual change on the Pacific coast is about 4′, and in New England about 3′. At London in 1660 the magnetic declination was zero, and it attained its maximum westerly value of 24° in 1810; in 1900 it had decreased again to 15°.

369. Agonic Lines. — Lines drawn through places where the needle points true north are called *agonic lines*. The one in North America runs from the magnetic pole southward across the eastern end of Lake Superior, thence near Lansing, Michigan, Columbus, Ohio, through West Virginia and South Carolina, and it leaves the mainland near Charleston on its way to the magnetic pole in the southern hemisphere. East of this line the needle points west of north; west of it, it points east of north. Lines passing through places of the same declination are called *isogonic lines*.

Questions

1. How would you determine which is the north pole of a magnet?

2. Given two steel bars exactly alike in every respect except that one is magnetized. Select the magnetized one.

3. How would you magnetize a sewing needle so that the eye end shall be the north pole?

4. Given two magnets that look alike in every respect. Determine which one is the more strongly magnetized.

5. Give two reasons for calling the earth a great magnet.

6. If a magnet attracts iron, why does not a floating iron vessel if left to itself move toward the north?

7. Does it make any difference in the construction of a pocket compass whether it is mounted in a brass case or an iron one?

8. Will the steel I-beams supporting a floor have any effect on the indications of a magnetic needle near them?

9. If the earth's magnetism tends to make the north pole of a magnetic needle dip downward, how is it that compass needles are horizontal?

10. In what direction does the magnetic needle point at the magnetic pole in the northern hemisphere? In what direction does a dipping needle stand? Is the polarity of the earth's magnetism in the northern hemisphere the same as that of the north pole of a magnet or that of the south pole?

CHAPTER XI

ELECTROSTATICS

I. ELECTRIFICATION

370. Electrical Attraction. — Rub a dry flint glass rod with a silk pad and bring it near a pile of pith balls or bits of paper. They will at first be attracted and then repelled (Fig. 307).

The simple fact that a piece of amber (a fossil gum) rubbed with a flannel cloth, acquires the property of attracting bits of paper, pith, or other light bodies, has been known since about 600 B.C.; but it seems not to have been known for the following 2200 years that any bodies except amber and jet were capable of this kind of excitation. About 1600 Gilbert discovered that a large number of substances possess the same property. These he called *electrics* (from the Greek word for amber, *electron*). A body excited in this manner is said to be *electrified*, its condition is one of *electrification*, and the invisible agent to which the phenomenon is referred is *electricity*.

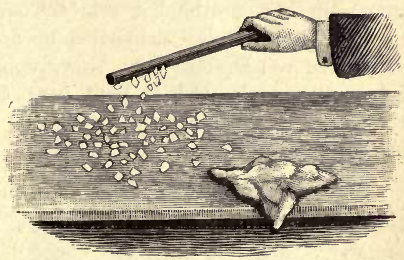


Fig. 307

371. Electrical Repulsion. — Suspend several pith balls from a glass rod or insulated hook (Fig. 308). Touch them with an electrified

glass tube. They are at first attracted but they soon fly away from the tube and from one another. When the tube is removed to a distance, the balls no longer hang side by side, but keep apart for some little time. If we bring the hand near the balls they will move toward it as if attracted, showing that the balls are electrified.

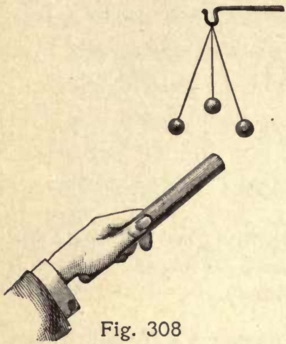


Fig. 308

This experiment shows that bodies become electrified by coming in contact with electrified bodies, and that electrification may show itself by repulsion as well as by attraction.

372. Attraction Mutual. — Electrify a flint glass tube by friction with silk, and hold it near the end of a long wooden rod resting in a wire stirrup suspended by a silk thread (Fig. 309). The suspended rod is attracted. Now, replace the rod by the electrified tube. When the rod is held near the rubbed end of the glass tube, the latter moves as if attracted by the former.

The experiment teaches that each body attracts the other; that is, that *the action is mutual.*

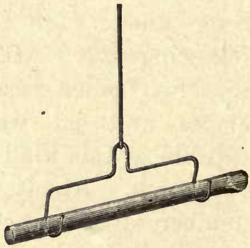


Fig. 309

373. Two Kinds of Electrification. — Rub a glass tube with silk and suspend it as in Fig. 309. Rub a second glass tube and hold it near one end of the suspended one. The suspended tube will be repelled. Bring near the suspended tube a rod of sealing wax rubbed with flannel. The suspended tube is now attracted. Repeat these tests with an electrified rod of sealing wax in the stirrup instead of the glass tube. The electrified sealing wax will repel the electrified sealing wax, but there will be attraction between the sealing wax and the glass tube.

The experiment shows that there are *two kinds of electrification:* one developed by rubbing glass with silk, and the other by rubbing sealing wax with flannel. To the former Benjamin Franklin gave the name *positive electrification;* to the latter, *negative electrification.*

374. First Law of Electrostatic Action. — It was seen in the last experiment that there is repulsion between electrified glass tubes, and that electrified sealing wax attracts electrified glass. These facts are expressed by the following law: —

Like electrical charges repel each other: unlike electrical charges attract each other.

375. The Electroscope. — An instrument for detecting electrification and for determining its kind is called an *electroscope.* Fig. 310 illustrates a convenient form. The rectangular vessel has two opposite faces of glass, metal ends, and a wooden or ebonite base. A brass rod, terminating on the outside in a ball or disk, passes through a sulphur, amber, or shellac plug set in the top of the case. The indicating system consists of a rigid piece of flat brass, to which is attached a narrow strip of gold leaf or other metal foil. A scale drawn on mica

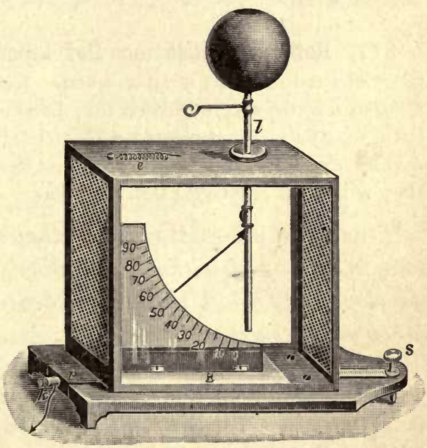


Fig. 310

is sometimes placed adjacent to the foil to measure its displacement. If the knob be touched with an excited glass tube, the foil will be repelled by the stem because the two are similarly electrified.

376. Charging an Electroscope. — To charge an electroscope an instrument called a *proof plane* is needed. It consists of a small metal disk attached to an ebonite handle (Fig. 311). To use it touch the disk to the electrified body and then apply it to the knob of the electroscope. The angular separation of the foil from the stem will indicate the intensity of the electric charge imparted. This method is known as *charging by contact* in distinction from *charging by induction* to be described later (§ 383).

Fig. 311

377. Both Electrifications Developed Together. — Glue a small piece of fur to a short strip of wood. Rub a rod of hard rubber or a stick of sealing wax with this fur; keep the two in contact and bring them up to a charged electroscope. There will be no change in the divergence of the gold leaf. Now test the rod and the fur separately; they will show opposite electrifications.

This experiment shows (1) *that one kind of electrification is not developed without the other; and* (2) *that they are developed in equal quantities, because they neutralize each other when together.*

378. Conductors and Nonconductors. — Fasten a smooth metallic button to a rod of sealing wax and connect the button with the knob of the electroscope by a fine copper wire, 50 to 100 cm. long. Hold the sealing wax in the hand and touch the button with an electrified glass tube. The divergence of the leaf indicates that it is electrified. If we repeat the experiment, using a silk thread in place of the wire, no such effect will be produced.

All substances may be roughly classed under two heads, *conductors* and *nonconductors*. In the former if one point of the body is electrified by any means, the electrification spreads over the whole body, but in a nonconductor the electrification is confined to the vicinity of the point where it is excited. Nonconductors are commonly called *insulators*. Substances differ greatly in their conductivity, so that it is not possible to divide them sharply into two classes. There is no substance that is a perfect conductor; neither is there any that affords perfect insulation. Metals, carbon, and the solution of some acids and salts are the best conductors. Among the best insulators are paraffin, turpentine, silk, sealing wax, India rubber, gutta-percha, dry glass, porcelain, mica, shellac, spun quartz fibers, and liquid oxygen. Some insulators, like glass, become good conductors when heated to a semi-fluid condition.

379. Probable Nature of Electrification. — It was suggested by Faraday that the electrification of a body is a strained condition of the ether which surrounds it and pervades it. This conclusion is supported by many facts, such as action at a distance, rupture of bodies by overcharging, etc. Conductors differ from insulators in this: in the former, the molecular mobility is such that this state of strain is continually giving way, while in the latter considerable distortion is possible before the molecules yield to the strain. The phenomena of attraction and repulsion exhibited by electrified bodies are due to the attempt of the strained ether in and around the bodies to return to its normal condition. In producing electrification, work is done in distorting the medium; hence electrification is a form of potential energy.

II. ELECTROSTATIC INDUCTION

380. Electrification by Induction. — Rub a glass tube with silk and bring it near the top of an electroscope. The leaves begin to diverge when the tube is some distance from the knob (Fig. 312) and the amount of divergence increases as the tube approaches. When the tube is removed the leaves collapse.

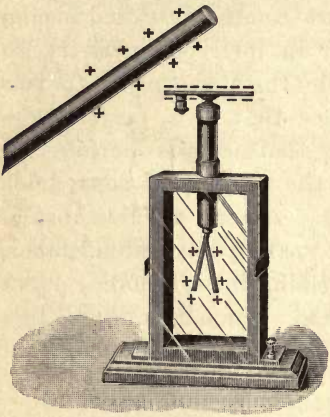


Fig. 312

Since the leaves do not remain apart, it is evident that there has been no transfer of electrification from the tube to the electroscope. The electrification produced in the electroscope when the electrified body is brought near it is owing to *electrostatic induction.* That such an effect should occur is easily understood when we recall Faraday's view of electrification as a distortion of the ether about the body. Evidently, then, any body placed within this *electrical field* should be electrified.

381. Sign of the Induced Charges. — Lay a smooth metallic ball on a dry plate of glass. Connect it with the knob of the electroscope by means of a stout wire with an insulating handle (Fig. 313). The ball and the electroscope now form one continuous conductor. Bring near the ball an electrified glass tube; the leaves of the electroscope diverge. Before withdrawing the excited tube, remove the wire conductor. The electroscope remains charged, and it will be found to be positive. A similar test made of the ball will show that it is negatively charged.

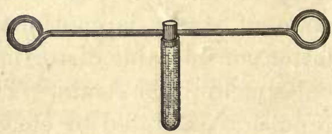


Fig. 313

Hence, we learn that *when an electrified body is brought near an object it induces the opposite kind of electrification on the side next it and the same kind on the remote side.*

382. Equality of the Induced Charges. — Put a metallic vessel, like the one shown in Fig. 315, on a glass plate and connect it with the knob of an electroscope by a fine wire. Attach a silk thread to a metallic ball about an inch in diameter, and charge the ball, holding it by the silk thread. Lower the charged ball into the vessel and observe that the leaves of the electroscope diverge as the ball enters the vessel. The divergence increases till the ball has been lowered perhaps two inches below the top, and then remains the same, even when the ball touches the bottom and communicates its charge to the insulated vessel.

Suppose the ball charged positively; it induces a negative charge on the interior of the vessel and repels a positive charge to the outside. This positive charge is equal to the charge on the ball, for the divergence of the leaves does not change when the ball gives up its charge to the vessel. The charge on the ball neutralizes the equal negative charge on the interior, leaving the equal positive charge on the exterior.

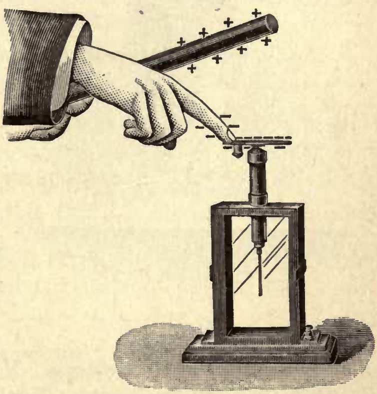


Fig. 314

Discharge the electroscope and charge the ball a second time. After it has been lowered into the insulated vessel without touching it, place the finger on the ball of the electroscope; the leaves will collapse. Remove the finger and lift the ball by the silk thread; the leaves will again diverge. Lower the ball again till it touches the vessel, and the leaves will again collapse. The charge induced on the inside is exactly neutralized by the inducing charge on the ball.

Hence, *the induced and the inducing charges are equal to each other.*

383. Charging an Electroscope by Induction. — Hold a finger on the ball of the electroscope and bring near it an electrified glass tube (Fig. 314). Remove the finger before taking away the tube; the electroscope will be charged negatively. If a stick of electrified sealing wax be used instead of the glass tube, the electroscope will be charged positively.

III. ELECTRICAL DISTRIBUTION

384. The Charge on the Outside of a Conductor. — Place a round metallic vessel of about one liter capacity on an insulated support (Fig. 315). Electrify strongly and test in succession both the inner and the outer surface, using a proof plane to convey the charge to the electroscope. The inner surface will give no sign of electrification.

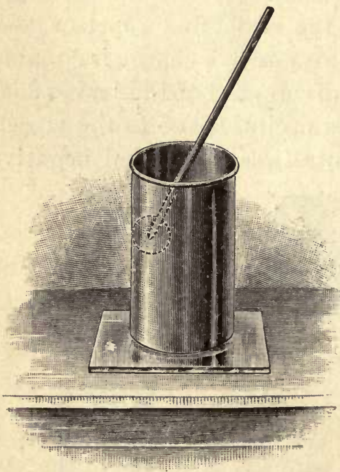


Fig. 315

Hence, it appears that *the electrical charge of a conductor is confined to its outer surface.*

385. Effect of Shape. — Charge electrically an insulated egg-shaped conductor (Fig. 316). Touch the proof plane to the large end, and convey the charge to the electroscope. Notice the amount of divergence of the leaves. Test the side and the small end of the conductor in the same way. The greatest divergence of the leaves will be produced by the charge from the small end and the least from the sides.

Fig. 316

The experiment shows that the surface density is greatest at the small end of the conductor.

By *surface density* is meant the quantity of electrification on a unit area of the surface of the conductor.

The distribution of the charge is, therefore, affected by the shape of the conductor, the surface density being greater the greater the curvature.

386. Action of Points. — Attach a sharp-pointed rod to one pole of an electrical machine (§ 399), and suspend two pith balls from the same pole. When the machine is worked there will be little or no separation of the pith balls. Hold a lighted candle near the pointed rod; the candle flame will be blown away as by a stiff breeze (Fig. 317).

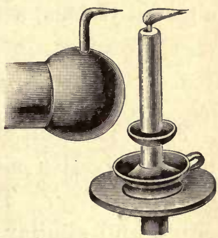


Fig. 317

The experiment shows that an electric charge is carried off by pointed conductors. This conclusion might have been drawn from the preceding experiment. When the curvature of the egg-shaped conductor becomes very great so that the surface becomes pointed, the surface density also becomes great and there is an intense field of electric force in the immediate neighborhood. The air particles touching the point become heavily charged and are then repelled; other particles take their place and are in turn repelled and form an *electrical wind*. The conductor gives up its charge to the repelled particles of air.

Questions

1. What would be the effect of replacing the ball of an electroscope by a sharp point?

2. Why is the gold leaf of an electroscope inclosed in a case?

3. What kind of a handle must a proof plane have? Why?

4. Why must electrical apparatus be thoroughly dry to work well?

5. If a long silk ribbon is doubled and then stroked between the folds of a piece of fur, the two halves will repel each other. Why?

6. Why does not a metal rod held in the hand and rubbed with silk show electrification? Can it be made to do so, and how?

7. Place an electroscope in a cage of wire netting. Why is it not affected by an electrified glass rod held near it?

8. How is it possible to electrify an electroscope, using only a silk handkerchief?

9. If electrification is a form of energy, whence its source in the case of an electrified glass rod?

10. If a pith ball were separated from an electrified glass rod by a perfect vacuum, would there be any attraction?

IV. ELECTRIC POTENTIAL AND CAPACITY

387. The Unit of Electrification or Charge. — Imagine two minute bodies similarly charged with equal quantities of electricity. They will repel each other. If the two equal and similar charges are one centimeter apart in air, and if they repel each other with a force of one dyne, then the charges are both unity. *The electrostatic unit of quantity is that quantity which will repel an equal and similar quantity at a distance of one centimeter in air with a force of one dyne.* It is necessary to say "in air" because, as will be seen later, the force between two charged bodies depends on the nature of the medium between them (§ 393).

This electrostatic unit is very small and has no name. In practice, a larger unit, called the *coulomb*, is employed. It is equal to 3×10^9 electrostatic units.

388. Potential Difference. — The analogy between *pressure* in hydrostatics and *potential* in electrostatics is a very convenient and helpful one. Water will flow from the

tank *A* to the tank *B* (Fig. 318) when the stopcock *S* in the connecting pipe is open if the hydrostatic pressure at *a* is greater than at *b*; and the flow is attributed directly to this difference of pressure.

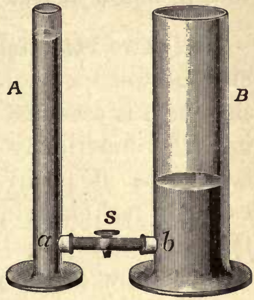


Fig. 318

In the same way, if there is a flow of positive electricity from *A* to *B* when the two conductors are connected by a conducting wire *r* (Fig. 319), the electrical potential is said to be higher at *A* than at *B*, and the difference of electrical potential between *A* and *B* is assigned as the cause of the flow. In both cases the flow is in the direction of the difference of pressure or difference of potential, irrespective of the fact that *B* may already contain more water because of its large cross section, or a greater electric charge because of its larger capacity.

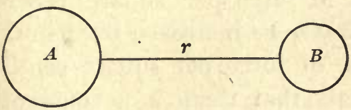


Fig. 319

If the electric charges in a system of connected conductors is in a stationary or static condition, there is then no potential difference between different points of the system.

The *potential difference* between two conductors is measured by the work done in carrying a unit electric charge from the one to the other.

389. Unit Potential Difference. — There is unit potential difference between two conductors when one erg of work is required to transfer the unit electric charge from the one conductor to the other. This is called the absolute unit; for practical purposes it has been found more con-

venient to employ a unit of potential difference (P.D.), which is $\frac{1}{300}$ of the absolute unit, and which is called the *volt*, in honor of the Italian physicist, Alessandro Volta.

390. Zero Potential. — In measuring the potential difference between a conductor and the earth, the potential of the earth is assumed to be zero. The potential difference is then numerically the *potential of the conductor.* If a conductor of positive potential be connected with the earth by an electric conductor, the positive charge will flow to the earth. If the conductor has a negative potential, the flow of the positive quantity will be in the other direction.

391. Electrostatic Capacity. — If water be poured into a cylindrical jar until it is 10 cm. deep, the pressure on the bottom of the jar is 10 gm. of force per square centimeter. If the depth of the water be increased to 20 cm., the pressure will be 20 gm. of force per square centimeter (§ 48). It thus appears that there is a constant relation between the quantity of water Q and the pressure P; that is, $\frac{Q}{P} = C$, a constant.

Again, if a gas tank be filled with gas at atmospheric pressure, it will exert a pressure of 1033 gm. of force per cm^2. (§ 68). If twice as much gas be pumped into the tank, the pressure by Boyle's law (§ 74) will be doubled at the same temperature; that is, there is a constant relation between the quantity of gas Q and the pressure P of the gas in the tank, or $\frac{Q}{P} = C$, a constant as before.

In the same way, if an electric charge be given to an insulated conductor, its potential will be raised above that of the earth. If the charge be doubled, the potential

Alessandro Volta (1748–1827) was born at Como, Italy. He was professor of physics at the University of Pavia, and was noted for his researches and investigations in electricity. The voltaic cell, the electroscope, the electrical condenser, and the electrophorus are due to his genius.

Georg Simon Ohm (1789–1854) was born in Erlangen, Bavaria, and was educated at the University of that town. He began his investigations by measuring the electrical conductivity of metals. In 1827 he announced the electrical law named in his honor, and in 1842 he was elected to a professorship in the University of Munich.

difference between the conductor and the earth will also be doubled. Precisely as in the case of the water and of the gas, there is a constant relation between the amount of the charge Q and the potential difference V between the conductor and the earth; that is, $\frac{Q}{V} = C$. This ratio or constant C is the *electrostatic capacity* of the conductor.

If $V = 1$, then $C = Q$; from which it follows that *the electrostatic capacity of a conductor is equal to the charge required to raise its potential from zero to unity.*

From $\frac{Q}{V} = C$ we have $Q = CV$, and $V = \frac{Q}{C}$. (Equation 34.)

392. Condensers. — Support a metal plate in a vertical position on an insulating base (Fig. 320.) Connect it to the knob of an electroscope by a fine copper wire. Charge the plate until the leaves of the electroscope show a wide divergence. Now bring an uninsulated conducting plate near the charged one and parallel to it. The divergence of the leaves will decrease; remove the uninsulated plate, and the divergence will increase again.

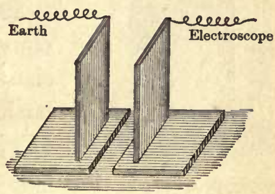


Fig. 320

The capacity of an insulated conductor is not dependent on its dimensions alone, but it is increased by the presence of another conductor connected with the earth. The effect of this latter conductor is to decrease the potential to which a given charge will raise the insulated one. Such an arrangement of parallel conductors separated by an insulator or *dielectric* is called a *condenser*.

A condenser is a device which greatly increases the charge on a conductor without increasing its potential. In other words, the plate connected with the earth greatly increases the capacity of the insulated conductor.

393. Influence of the Dielectric. — Charge the apparatus of the last experiment, with the uninsulated plate at a distance of about 5 cm. from the charged plate and parallel to it, thrust suddenly between the two a cake of clean paraffin as large as the metal plates or larger, and from 2 to 4 cm. thick. Note that the leaf of the electroscope (Fig. 310) collapses slightly. Remove the paraffin quickly, and the divergence will increase again. A cake of sulphur will produce a more marked effect on the divergence of the leaf.

The presence of the paraffin or the sulphur increases the capacity of the condenser and, hence, decreases its potential, the charge remaining the same. Paraffin and sulphur, as examples of dielectrics, are said to have a larger *dielectric capacity* or *dielectric constant* than air. Glass has a dielectric capacity from four to ten times greater than air.

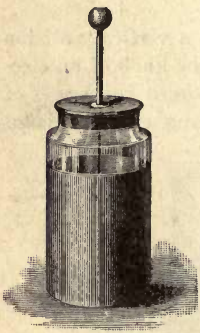


Fig. 321

394. The Leyden Jar is a common and convenient form of condenser. It consists of a glass jar coated part way up, both inside and outside, with tin-foil (Fig. 321). Through the wooden or ebonite stopper passes a brass rod, terminating on the outside in a ball and on the inside in a metallic chain which reaches the bottom of the jar. The glass is the dielectric separating the two tin-foil conducting surfaces.

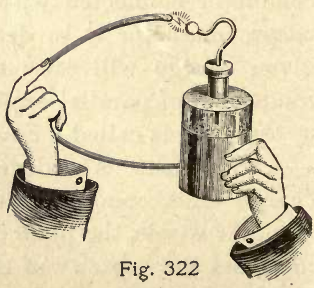


Fig. 322

395. Charging and Discharging a Jar. — To charge a Leyden jar connect the outer surface to one pole of an electrical machine (§ 399), either by

a metallic conductor or by holding the jar in the hand. Hold the ball against the other pole. To discharge a Leyden jar bend a wire into the form of the letter V. With one end of the wire touching the *outer* surface of the jar (Fig. 322), bring the other around near the ball, and the discharge will take place.

396. Seat of Charge. — Charge a Leyden jar made with movable metallic coatings (Fig. 323) and set it on an insulating stand. Lift out the inner coating, and then, taking the top of the glass vessel in one hand, remove the outer coating with the other. The coatings now exhibit no sign of electrification. Bring the glass vessel near a pile of pith balls; they will be attracted to it, showing that the glass is electrified. Reach over the rim with the thumb and forefinger and touch the glass. A slight discharge may be heard. Now build up the jar by putting the parts together; the jar will still be highly electrified and may be discharged in the usual way.

Fig. 323

This experiment was devised by Franklin; it shows that electrification is a phenomenon of the glass, and that the metallic coatings serve merely as conductors, making it possible to discharge all parts of the glass at once.

397. Theory of the Leyden Jar. — A Leyden jar may be broken by over charging, may be discharged by heating, and if heavily charged is not completely discharged by connecting the two coatings; if left standing a few seconds, the two coatings gradually acquire a small potential difference and a second small discharge may be obtained, known as the *residual charge.* It appears, therefore, that the glass of a charged jar is strained or distorted; like a

twisted glass fiber, it does not return at once to its normal state when released.

The two surfaces of the glass are oppositely electrified, the one charge acting inductively through the glass and producing the opposite electrification on the other surface. The two charges are held inductively and are said to be "bound," in distinction from the charge on an insulated conductor, which is said to be "free."

Questions

1. Why is not a Leyden jar standing on a cake of paraffin discharged by touching the ball with the finger?

2. Why is the capacity of a Leyden jar increased by connecting its outer surface with the earth? Is the result the same if one coating is connected to one pole of an electrical machine and the other coating to the other pole?

3. Why will a dust-covered electrified body soon lose its charge?

4. Cuneus tried to charge a bowl of water by holding it in his hand while a chain from an electrical machine dipped into it. When he lifted out the chain he got a severe shock. Why?

5. Why is it unsafe to touch the ball first when discharging a Leyden jar by means of a bent wire? Would it make any difference if the wire were held by an insulating handle?

6. When a charged proof plane touches the ball of an electroscope does it give up all its charge?

7. When a charged proof plane touches the inside of a hollow insulated conductor, does it give up all its charge? Why?

8. If a condenser whose capacity is 200 *c.g.s.* units is charged with 2000 *c.g.s.* units of electricity, what is the potential difference in *volts* between its two coatings (§ 391)?

V. ELECTRICAL MACHINES

398. The Electrophorus. — The simplest induction electrical machine is the *electrophorus* (Fig. 324), invented by Volta. A cake of resin or disk of vulcanite (A) rests

in a metallic base (B). Another metallic disk or cover (C) is provided with an insulating handle (D). The resin or vulcanite is electrified by rubbing with dry flannel or striking with a catskin, and the metal disk is then placed on it. Since the cover touches the nonconducting resin or vulcanite (A) in a few points only, the negative charge due to the friction is not removed. The two disks with the film of air between them form a condenser (§ 392) of great capacity.

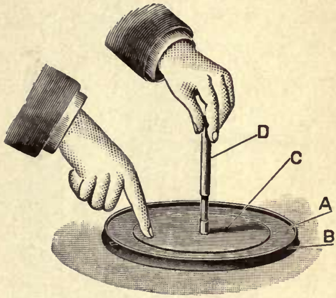


Fig. 324

Touch the cover momentarily with the finger, and the repelled negative charge passes to the earth, leaving the cover at zero potential. Lift it by the insulating handle, the positive charge becomes free (§ 397), and a spark may be drawn by holding the finger near it. This operation may be repeated an indefinite number of times without sensibly reducing the charge on the vulcanite.

When the cover is lifted by the insulating handle, work is done against the electrical attraction between the negative charge on the vulcanite and the positive on the cover. The energy of the charged cover represents this work. *The electrophorus is, therefore, a device for the continuous transformation of mechanical work into the energy of electric charges.*

399. Influence Electrical Machines. — There are many influence or induction electrical machines, but it will suffice to describe only one as the principle is always the same.

The Holtz machine, as modified by Toepler and Voss, is illustrated in Fig. 325. There are two glass plates, e'

and *e*, about 5 mm. apart, the former stationary and the latter turning about an insulated axle by means of the crank *h* and a belt. The stationary plate supports at

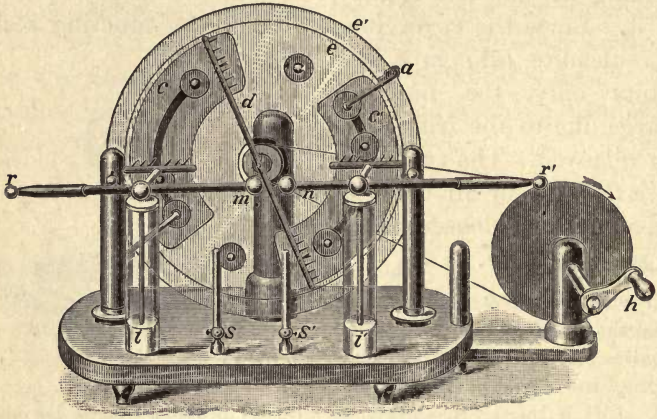


Fig. 325

the back two paper sectors, *c* and *c'*, called *armatures.* Between them and the stationary plate *e'* are disks of tin-foil connected by a narrow strip of the same material. The disks are electrically connected with two bent metal arms, *a* and *a'* (opposite *a*), which carry at the other end tinsel brushes long enough to rub against low brass buttons cemented to small tin-foil disks, called *carriers*, on the front of the *revolving* plate. Opposite the paper sectors and facing them are two metal rods with several sharp-pointed teeth set close to the revolving plate, but not touching the metal buttons and carriers. The diagonal neutralizing rod *d* has tinsel brushes in addition to the sharp points. The two insulated conductors, terminating in the balls, *m* and *n*, have their capacity increased by connection with the inner coating of two small

Leyden jars, i and i'; the outer coatings are connected under the base of the machine.

400. Action of the Machine. — There is usually enough excitation due to friction or to the contact of dissimilar substances to furnish the very slight initial charge on the armatures. These small charges are necessary to the operation of all induction machines. Suppose the two armatures, c and c' (Fig. 325), slightly charged, the one on the right positive. The armatures act by induction on the horizontal conductors opposite them; negative electricity escapes from the points on the right hand "comb" to the revolving plate, and positive from the left. The brushes on the neutralizing rod d are set so as to connect two carriers at opposite ends of the rod just before these carriers pass beyond the influence of the armatures c and c'. The carriers connected by the rod d thus acquire by induction positive and negative charges respectively, which they carry forward as the plate revolves until they are brought into momentary connection with the armatures by means of the brushes and the bent conductors a and a'. The carriers then deliver their small charges to the armatures. At the same time the revolving plate carries around the charges escaping by the points and gives them up, at least in part, to the conductors, a and a'. The potential difference between c and c' is thus increased by induction and the charges carried by the revolving plate until a discharge takes place between the balls m and n, when they are separated.

401. Experiments with Electrical Machines. — 1. *Attraction and repulsion.* Place a number of bits of paper on the cover of a charged electrophorus. Lift it by the insulating handle. The charged pieces of paper fly off the plate.

Three bells are suspended from a metal bar (Fig. 326). The middle one is insulated from the bar; the others are suspended by chains. Connect the bar to one pole of an electrical machine and the middle bell to the other. The small brass balls between the bells are suspended by silk cords; they swing to and fro between the bells, carrying positive charges in one direction and negative in the other. This apparatus, called the electrical chimes, is of interest because it was employed by Franklin in his lightning experiments to announce the electrification of the cord leading to the kite (§ 402).

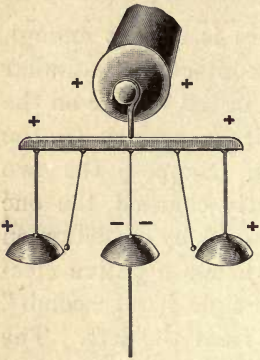


Fig. 326

2. *Discharge by points.* Connect an electrical tournique (Fig. 327) to one of the conductors of an electrical machine, the other conductor being grounded. When the machine is turned, the whirl rotates rapidly (§ 386).

3. *Mechanical effects.* Hold a piece of cardboard between the discharge balls of an electrical machine. It will be perforated by a spark and the holes will be burred out on both sides. A thin dry glass plate, or a thin test tube over a sharp point, may be perforated by a heavy discharge.

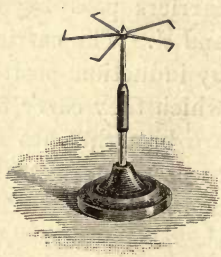


Fig. 327

4. *Heating effects.* Charge a Leyden jar and connect its outer coating with a gas burner by a chain or wire. Turn on the gas and bring the ball of the jar near enough to the opening in the burner to allow a spark to pass. The gas will be lighted by the discharge.

Fill a gas pistol (Fig. 328) with a mixture of coal gas and air. Discharge a Leyden jar through the mixture. It will explode and the cork or ball will be shot out with some violence.

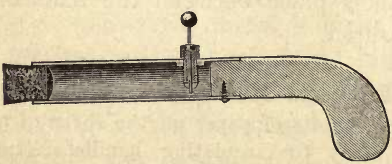


Fig. 328

5. *Magnetic effects.* — Wind insulated copper wire around a small glass tube (Fig. 329), and place inside the tube a piece of darning needle. Discharge a Leyden jar through the wire. The needle will be magnetized. A similar effect may be produced by placing a large sewing needle across a strip of tin-foil forming a part of the discharge circuit of a Leyden jar.

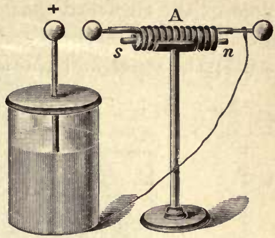


Fig. 329

VI. ATMOSPHERIC ELECTRICITY

402. Lightning.—Franklin demonstrated in 1752 that lightning is identical with the electric spark. He sent up a kite during a passing storm, and found that as soon as the hempen string became wet, long sparks could be drawn from a key attached to it, Leyden jars could be charged, and other effects characteristic of static electrification could be produced.

Lightning flashes are discharges between oppositely charged bodies. They occur either between two clouds or between a cloud and the earth. The rise of potential in a cloud causes a charge to accumulate on the earth beneath it. If the stress in the air reaches a value of about 400 dynes per cm.^{2}, the air breaks down, or is ruptured, like any other dielectric, and the two opposite charges unite in a long zigzag flash. A lightning flash allows the strained medium to return to equilibrium. The coming together of the air surfaces, which are separated in the rupture, produces a violent crash of *thunder*.

403. The Lightning Rod. — Support two round metal plates, T and T', one above the other and a few centimeters apart (Fig. 330). The upper plate must be carefully insulated except from the

pole of the electrical machine and the inner coating of a Leyden jar L. Two of the short rods on the lower plate terminate in small balls; the other and shortest one is pointed. When the machine is worked, the tension between the plates increases, but it is difficult to make a spark pass; if one does pass, it will strike the pointed rod.

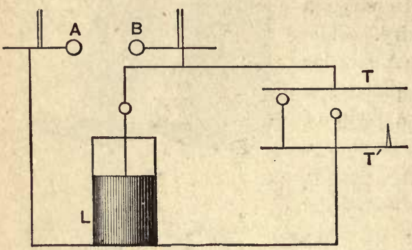


Fig. 330

The experiment illustrates the protection afforded by a pointed conductor.

A lightning rod should conform to the following requirements :

First. It should be perfectly continuous, of sufficient size to resist fusion, and made preferably of strands of wire twisted together as a cable. Iron cables are as good as copper ones.

Second. The upper end should terminate in points and should be higher than adjacent parts of the building. The lower end should pass down into the earth until it enters a moist conducting stratum.

Third. The rod should be fastened to the building without insulators, and all metal parts of the roof should be connected with the main conductor. It is better to have two or three descending rods than one, and all the points and rods should be connected together as a network.

404. Oscillatory Discharge. — When a Leyden jar is highly charged, the potential difference between its coatings increases until the dielectric between the discharge terminals suddenly breaks down and a spark passes. This discharge usually consists of several oscillations or to-and-fro discharges, like the vibrations of an elastic

Benjamin Franklin (1706–1790) was born at Boston, Massachusetts. In his twentieth year he was apprenticed to his elder brother in the printing business. When forty years of age he saw some electrical experiments performed with a glass tube. These excited his curiosity and he began experimenting for himself. In less than a year he had discovered the discharging effects of points and worked out a theory of electricity, known as the "one-fluid theory." He explained the charged Leyden jar, established the identity of lightning and the electric spark, invented an electric machine, and introduced the lightning rod as a protection against lightning. He was distinguished as a statesman, diplomatist, and scientist. He founded the American Philosophical Society and the University of Pennsylvania.

system, or the surges of a mass of water after sudden release from pressure. Imagine a tank with a partition across the middle and filled on one side with water. If a small hole be made in the partition near the bottom, the water will slowly reach the same level on both sides without agitation; but if the partition be suddenly removed, the first violent subsidence will be succeeded by a return surge, and the to-and-fro motion of the water will continue with decreasing violence until the energy is all expended.

A series of similar surges occurs when a condenser is suddenly discharged by the breaking down of the dielectric. The oscillatory character of such electric discharges was discovered by Joseph Henry in 1842. Its importance has been recognized only in recent times. Similar electric oscillations probably take place in some lightning flashes.

405. The Aurora. — The *aurora* is due to silent discharges in the upper regions of the atmosphere.[2] Within the arctic circle it occurs almost nightly, and sometimes with indescribable splendor. The illumination of the aurora is due to positive discharges passing from the higher regions of the atmosphere to the earth. In our latitude these silent streamers in the atmosphere are infrequent. When they do occur they are accompanied by great disturbances of the earth's magnetism and by earth currents. Such magnetic disturbances sometimes occur at the same time in widely separated portions of the earth.

$\frac{F-32}{180} = \frac{C}{100}$

$\frac{98-32}{1.80} = C$

CHAPTER XII

ELECTRIC CURRENTS

I. VOLTAIC CELLS

406. An Electric Current. — When a condenser is discharged through a wire, there is produced in and around the wire a state called an *electric current*. Electrification is a condition of strain in the dielectric; the electric current rapidly relieves this strain through the discharging conductor. If the state of strain is reproduced by the "generator" as fast as it is relieved by the conductor, the result is a continuous current. To accomplish this result work must be done, and therefore an electric current represents energy. The expression "current of electricity," was introduced when electricity was regarded as a fluid which flowed from higher to lower potential through a wire, just as water flows from a higher to a lower level through a pipe.

To produce a continuous electric current through a conductor a potential difference must be maintained between its terminals. One of the simplest means of doing this is the primary or voltaic cell.

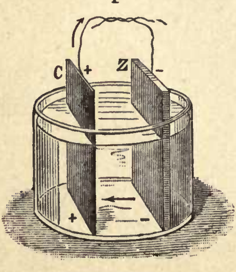


Fig. 331

407. The Voltaic Cell. — Support a heavy strip of zinc and one of sheet copper (Fig. 331) in dilute sulphuric acid (one part acid to twenty of water). After the zinc has been in the acid a short time, it should be amalgamated by rubbing it with mercury.

There will be no apparent change when the plates are replaced in the acid, until the two are connected with a copper wire; a multitude of bubbles of hydrogen gas will then immediately be given off at the surface of the copper plate. The action ceases as soon as the wires are disconnected. If the action is continued for some time, the zinc will waste away, while the copper is not affected.

Such a combination of two conductors, immersed in a compound liquid, called an *electrolyte*, which is capable of reacting chemically with one of the conductors, is called a *voltaic cell.* The name is derived from Volta of Padua, who first described such a cell in 1800.

408. Plates Electrically Charged. — In a condensing electroscope the ball at the top is replaced by a brass disk coated with thin shellac varnish as an insulator. Resting on it is a second disk to which is fitted an insulating handle. The two disks with the shellac varnish between them form a condenser of considerable capacity.

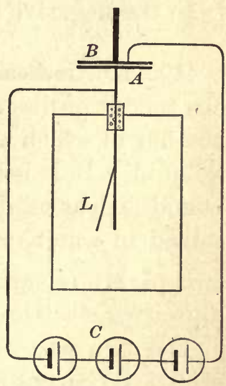


Fig. 332

Connect the wire leading from the copper plate of two or three voltaic cells C in series (§ 437) to the lower disk A of the electroscope, and the wire from the zinc plate to the upper disk B (Fig. 332). Disconnect the wires, handling them one at a time by means of a good insulator so as not to discharge the condenser, and then lift the top disk. The leaf L of the electroscope will diverge, and a test with an electrified glass rod will show that the electroscope is charged positively.. This positive charge was derived from the copper strip of the cell. Repeat the experiment with the zinc plate connected to the lower disk; the result will be a negative charge on the gold leaf.

It is clear from this experiment that *the plates of a voltaic cell and the wires leading from them are electrically charged, the copper positively and the zinc negatively.* The

conducting rods, plates, or cylinders in a voltaic cell are called *electrodes*, the *copper* the *positive electrode* or *cathode* and the *zinc* the *negative electrode* or *anode.* The electric current leaves the electrolyte by the cathode (meaning *the way out*) and enters it by the anode (meaning *the way in*).

409. The Circuit. — The *circuit* of a voltaic cell comprises the entire path traversed by the current, including the electrodes and the liquid in the cell as well as the external conductor. *Closing the circuit* means joining the two electrodes by a conductor; *breaking* or *opening the circuit* is disconnecting them. The flow of current in the external circuit is from the positive electrode (copper) to the negative (zinc), and in the internal part of the circuit from the negative electrode to the positive (Fig. 331).

410. Electrochemical Actions in a Voltaic Cell. — The modern theory of dissociation furnishes an explanation of the manner in which an electric current is conducted through a liquid. It is briefly as follows: When a chemical compound such as sulphuric acid (H_2SO_4),* for example, is dissolved in water, some of the molecules at least split into two or three parts ~~($\overset{+}{H_2}$ and $\overset{-}{SO_4}$, for example)~~, one part having a positive electrical charge and the other a negative one.

The two parts of the dissociated substance with their electrical charges are called *ions* (from a Greek word meaning *to go*). An *electrolyte* is a compound capable of such dissociation into ions. It conducts electricity only by means of the migration of the ions resulting from the splitting in two of the molecules. The separated ions convey their charges with a slow and measurable velocity through

* Each molecule of sulphuric acid is composed of two atoms of hydrogen (H_2), one of sulphur (S), and four of Oxygen (O_4).

the liquid. Electropositive ions, such as zinc and hydrogen, carry positive charges in one direction, electronegative ions, such as "sulphion" ($\overline{SO_4}$), carry negative charges in the opposite direction, and the sum of the two kinds of charges carried through the liquid per second is the measure of the current.

Fig. 333 represents a section of a voltaic cell with the electropositive and electronegative ions. When the circuit is closed and a current flows, zinc from the zinc plate enters the solution as electropositive ions ($\overset{+}{Zn}$), while the positive hydrogen ions migrate toward the copper plate or cathode, and the sulphions toward the zinc plate. ~~The $\overline{SO_4}$~~ ions carry negative charges to the zinc plate, so that it becomes charged negatively, while the ~~$\overset{+}{H_2}$ ions~~ carry positive charges to the copper plate and it becomes charged positively. Zinc from the zinc plate thus goes into solution as zinc sulphate ($ZnSO_4$), and hydrogen when it has given up its positive charge is set free as gaseous hydrogen on the copper plate. Some prefer to say that when the zinc ions with their positive charge leave the zinc plate, the equivalent negative is left behind to charge the zinc electrode. The zinc ions unite with the sulphions to form neutral zinc sulphate. Thus, while the zinc *ions* are electropositive and carry positive charges, the zinc *plate* is charged negatively.

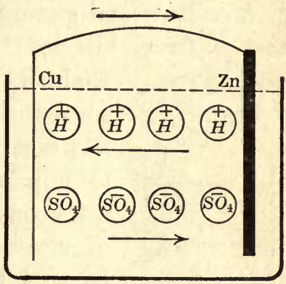


Fig. 333

411. Electromotive Force. — Imagine a rotary pump which produces a difference of pressure between its inlet

and its outlet. Such a pump may cause water to circulate through a system of horizontal pipes against friction. In any portion of the pipe system the force producing the flow is the difference of water pressure between the ends of that portion. But the force is all applied at the pump, and this produces a pressure throughout the whole circuit. A voltaic cell is an electric generator analogous to such a pump.

A voltaic cell generates electric pressure called *electromotive force.* It does not generate electricity any more than the pump generates water, but it supplies the electric pressure to set electricity flowing. This electromotive force (E.M.F.) is numerically equal to the work which must be done to transport a unit quantity of electricity around the external circuit from A to B, through the zinc plate to Z, from Z through the liquid to C, and thence back to A (Fig. 334). Work is done in this transfer, because all conductors offer resistance to the passage of a current. The energy thus expended goes to heat the conductor.

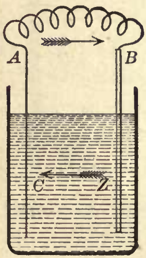


Fig. 334

412. Difference of Potential. — The difference of potential between two points, A and B, on the external conducting circuit is the work done in carrying a unit quantity of electricity from the one point to the other. The difference of potential between the electrodes of a voltaic cell when the circuit is closed is less than the E.M.F. of the cell by the work done in transferring unit quantity of electricity through the electrolyte. If E denotes this potential difference and Q the quantity conveyed, then the whole work done is the product EQ. But the quantity con-

veyed by a conductor per second is called the *strength of current*, I. The energy transformed in a conductor, therefore, when current I flows through it, under an electric pressure or potential difference of E units between its ends, is EI ergs per second.

413. Detection of Current. — Solder a copper wire to each of the strips of a voltaic cell, and connect the wires with some form of key to close the circuit. Stretch a portion of the wire over a mounted magnetic needle (Fig. 335), holding it parallel to it and as near as possible without touching. Now close the circuit; the needle is deflected, and comes to rest at an angle with the wire. Next form a rectangular loop of the wire, and place the needle within it. A greater deflection is now obtained. If a loop of several turns is formed, the deflection is still greater.

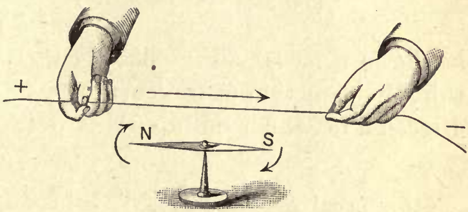


Fig. 335

A magnetic needle employed in this way becomes a *galvanoscope*, a detector of electric currents. This experiment, first performed by Oersted in 1819, shows that the region around the wire has magnetic properties during the flow of electricity through the wire. In other words, it is a magnetic field (§ 362).

414. Relation between the Direction of the Current and the Direction of Deflection. — Making use of the apparatus of § 413, compare the direction of the current through the wire with that in which the north pole of the needle turns. Cause the current to pass in the reverse direction over the needle; the deflection is reversed. Now hold the wire below the needle, and the direction of deflection is again reversed as compared with the deflection when the wire is held above the magnetic needle.

The direction of the deflection may always be predicted by the following rule: *Stretch out the right hand along the wire, with the palm turned toward the magnetic needle, and with the current flowing in the direction of the extended fingers. The outstretched thumb will then point in the direction in which the north pole of the needle is deflected* (Fig. 336). By the converse of this rule, the direction of the current may be inferred from the direction in which the needle is deflected.

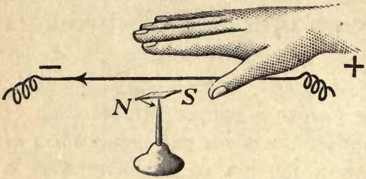


Fig. 336

415. Local Action. — Place a strip of commercial zinc in dilute sulphuric acid. Hydrogen is liberated during the chemical action, and after a few minutes the zinc becomes black from particles of carbon exposed to view by dissolving away the surface. If the experiment is repeated with zinc amalgamated with mercury, that is, by coating it with an alloy of mercury and zinc, there will be little or no chemical action. A strip of chemically pure zinc acts much like one amalgamated with mercury.

Thus we see that the amalgamation of commercial zinc with mercury changes its properties. If in the experiment with the simple voltaic cell, a galvanoscope is inserted in the circuit both before the zinc has been amalgamated and afterward, it will be found that a larger deflection will be obtained in the second case.

In a voltaic cell the chemical action which contributes nothing to the current flowing through the circuit is known as *local action.* It is probably due to the presence of carbon, iron, etc., in the zinc; these with the zinc form miniature voltaic cells, the currents flowing around in short

Hans Christian Oersted (1777–1851) was born at Rudkjöbing, Denmark, and received his education at the University of Copenhagen, afterward becoming professor in the University and polytechnic schools of that city. It was while holding this position that he discovered the action of the electric current on the magnetic needle, thus establishing the connection between electricity and magnetism which had long been sought by scientists. He also discovered that this magnetic action of the electric current takes place freely through a great many substances. Oersted wrote extensively for newspapers and magazines in an endeavor to make science popular.

circuits from the zinc through the liquid to the foreign particles and back to the zinc again.

This local action is prevented by amalgamating the zinc. The amalgam brings pure zinc to the surface, covers the foreign particles, and above all forms a smooth surface, so that a film of hydrogen clings to it and protects it from chemical action save when the circuit is closed.

416. Polarization. — Connect the poles of a voltaic cell to a galvanoscope and note the deflection. Let the cell remain in circuit with the galvanoscope for some time; the deflection will gradually become less and less. Now stir up the liquid vigorously with a glass rod, inserting the rod between the plates and brushing off the adhering gas bubbles; the deflection will increase nearly to its first value.

Fasten two strips of zinc and two of copper to a square board and immerse them in dilute sulphuric acid (Fig. 337). Join one zinc and one copper strip with a short wire for a few minutes. Then disconnect and join the two coppers to a galvanoscope. The direction of the deflection will be the same as if zinc were used in place of the copper strip coated with hydrogen. The hydrogen-coated copper acts like zinc and tends to produce a current through the electrolyte from it to the copper free from hydrogen.

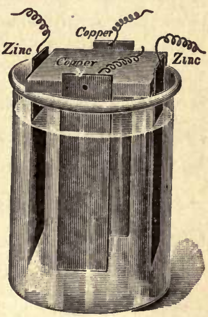


Fig. 337

The diminution in the intensity of the current is due to several causes, but the chief one is the film of hydrogen which gathers on the copper plate, causing what is known as the *polarization* of the cell. The hydrogen on the positive plate not only introduces more resistance to the flow of the current, but it diminishes the electromotive force to which this flow is due. The presence of hydrogen on the copper plate sets up an inverse E.M.F., which reduces the flow.

417. Remedies for Polarization. — Place enough pure mercury in a quart jar to cover the bottom, and hang above it a piece of sheet zinc. Fill the jar with a nearly saturated solution of salt water, and place in the mercury the exposed end of a copper wire insulated with gutta-percha, the mercury forming the positive electrode of the battery.

If now the circuit is closed through a telegraph sounder (§ 494) of ten or fifteen ohms resistance, the armature will at first be attracted strongly; but in the course of a few minutes it will be released and will be drawn back by the spring. Polarization has then set in to the extent that the current is insufficient to operate the instrument.

Next take a small piece of mercuric chloride ($HgCl_2$) no larger than the head of a pin, and drop it in on the surface of the mercury. The armature of the sounder will instantly be drawn down, showing that the current has recovered its normal value. The hydrogen has been removed by the chlorine of the mercuric chloride. In a few minutes the chlorine will be exhausted, and polarization will again set in. A little more of the chloride will again restore the activity of the cell. (This experiment was devised several years ago by Mr. D. H. Fitch.)

This illustrates a chemical method of reducing polarization. The hydrogen ions are replaced by others, such as copper or mercury, which do not produce polarization when they are deposited on the positive electrode; or else the positive electrode is surrounded with a chemical which furnishes oxygen or chlorine to unite with the hydrogen before it reaches the electrode. In both cases the electrode is kept nearly free from hydrogen.

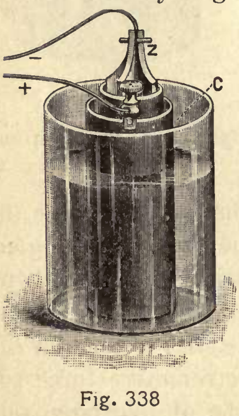


Fig. 338

418. The Daniell Cell. — *The Daniell Cell* in its most common form (Fig. 338) consists of a glass jar containing a saturated solution of copper sulphate ($CuSO_4$), and in it a cylinder C of

copper, which is cleft down one side. Within the copper cylinder is a porous cup of unglazed earthenware containing a dilute solution of zinc sulphate ($ZnSO_4$). In the porous cup also is the zinc prism *Z*. The copper sulphate must not be allowed to come in contact with the zinc electrode. The porous cup allows the ions to pass through its pores, but it prevents the rapid admixture of the two sulphates.

Both electrolytes undergo partial dissociation into ions; and when the circuit is closed, the zinc and the copper ions both travel toward the copper electrode. The zinc ions do not reach the copper, because zinc in copper sulphate replaces copper, forming zinc sulphate. The result is the formation of zinc sulphate at the zinc electrode and the deposition of metallic copper on the copper electrode. Polarization is quite completely obviated; and, so long as the circuit is kept closed, the mixing of the electrolytes by diffusion is slight. This cell must not be left on open circuit because the copper sulphate then diffuses until it reaches the zinc and causes a black deposit of copper oxide on it.

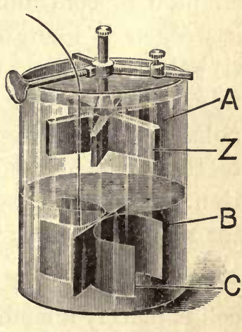


Fig. 339

419. The Gravity Cell. — This cell (Fig. 339) is a modified Daniell. The porous cup is omitted, and the partial separation of the liquids is secured by difference in density. The copper electrode *C* is placed at the bottom in saturated copper sulphate *B*, while the zinc *Z* is suspended near the top in a weak solution of zinc sulphate *A*, floating on top of the copper sulphate. The zinc should never be placed in the solution of copper sulphate. The

saturated copper sulphate is more dense than the dilute zinc salt, and so remains at the bottom, except as it slowly diffuses upward.

420. The Leclanché Cell consists of a glass vessel containing a saturated solution of ammonium chloride (sal ammoniac) in which stands a zinc rod and a porous cup (Fig. 340). In this porous cup is a bar of carbon very tightly packed in a mixture of manganese dioxide and graphite, or granulated carbon.

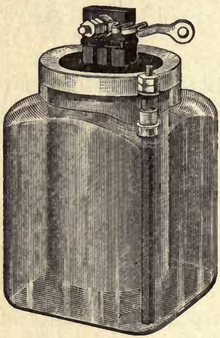


Fig. 340

The zinc is acted on by the chlorine of the ammonium chloride, liberating ammonia and hydrogen. The ammonia in part dissolves in the liquid, and in part escapes into the air. The hydrogen is slowly oxidized by the manganese dioxide. The cell is not adapted to continuous use, as the hydrogen is liberated at the positive electrode faster than the oxidation goes on, and hence the cell polarizes. If, however, it is allowed to rest, it recovers from polarization. The Leclanché cell is suitable for ringing electric bells.

421. The Dry Cell.— The "dry" cell is merely a modified Leclanché cell adapted for use in situations where cells with a liquid electrolyte could not be employed. The electrodes are zinc and carbon,

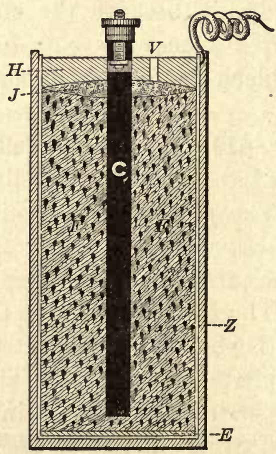


Fig. 341

the former being the cylindrical vessel containing the other parts of the cell. The zinc Z (Fig. 341) is contained in a cardboard case and has a thin insulating layer E at the bottom. The carbon plate is flat; it is shown edgeways in the figure. Between the two plates is a moist paste composed of zinc oxide, sal ammoniac, zinc chloride, plaster of Paris, and water. About twenty-five per cent of this paste is water. The oxide of zinc makes the composition porous, and so aids in the escape of gases and helps to prevent polarization. Graphite and manganese dioxide are also sometimes added to the paste. The cell is sealed with a bituminous compound H, through which is a vent V for the escape of gases.

The vent V is not necessary when a depolarizer as manganese di-oxide is used.

II. ELECTROLYSIS

422. Phenomena of Electrolysis. — Thrust platinum wires through the corks closing the ends of a V-tube (Fig. 342). Fill the tube nearly full with a solution of sodium sulphate colored with blue litmus. Pass through it a current for a few minutes. The liquid around the *anode* where the current enters will turn red, showing the formation of an acid; the liquid around the *cathode* where the current leaves the cell will turn a darker blue, showing the presence of an alkali.

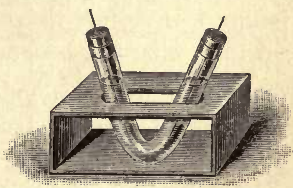


Fig. 342

The electric current in its passage through a liquid decomposes it. This process of decomposing a liquid by an electric current Faraday named *electrolysis;* the liquid decomposed he called the *electrolyte;* the parts of the separated electrolyte, *ions.* The current enters the electrolyte by the *anode* and leaves it by the *cathode.* The experiment illustrates certain polarity indicators, which

are made of a short tube filled with a suitable electrolyte and contain electrodes terminating in binding posts at the two ends (Fig. 343). When this is placed in circuit, the liquid turns red at one pole.

423. Electrolysis of Copper Sulphate. — Fill the V-tube of the last experiment about two-thirds full of a solution of copper sulphate. After the circuit has been closed a few minutes, the cathode will be covered with a deposit of copper, and bubbles of gas will rise from the anode. These bubbles are oxygen.

Fig. 343

When copper sulphate is dissolved in water it is dissociated to some extent. If, therefore, electric pressure is applied to the solution through the electrodes, the electropositive ions ($\overset{+}{Cu}$) are set moving from higher to lower potential, while the electronegative ions ($\overline{SO_4}$) carry their negative charges in the opposite direction. The $\overset{+}{Cu}$ ions are therefore driven against the cathode, and, giving up their charges, become metallic copper. The sulphions ($\overline{SO_4}$) go to the anode; and, giving up their charges, they take hydrogen from the water present, forming sulphuric acid (H_2SO_4) and setting free oxygen, which comes off as bubbles of gas. If the anode were copper instead of platinum, the sulphion would unite with it, forming copper sulphate, and copper would then be removed from the anode as fast as it is deposited on the cathode. The result of the passage of a current would then be the transfer of copper from the anode to the cathode. This is what takes place in the electrolytic refining of copper.

Thus the passage of an electric current through an

electrolyte is accomplished in the same way, whether it is in a voltaic cell or in an electrolytic cell.

424. Electrolysis of Water. — Water appears to have been the first *substance decomposed* by an electric current. Pure water does not conduct an appreciable current of electricity, but if it is acidulated with a small quantity of sulphuric acid, electrolysis takes place.

In Hofmann's apparatus (Fig. 344) the acidulated water is poured into the bulb at the top, and the air escapes by the glass taps until the tubes are filled. The electrodes at the bottom in the liquid are platinum foil. If a current is sent through the liquid, bubbles of gas will be liberated on the pieces of platinum foil. The gases collecting in the tubes may be examined by letting them escape through the taps. Oxygen will be found at the anode and hydrogen at the cathode; the volume of the hydrogen will be nearly twice that of the oxygen.

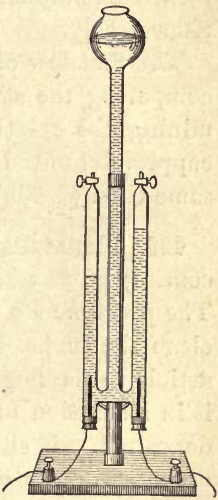


Fig. 344

425. Laws of Electrolysis. — The following laws of electrolysis were established by Faraday:

I. *The mass of an electrolyte decomposed by an electric current is proportional to the quantity of electricity conveyed through it.*

The mass of an ion liberated in one second is, therefore, proportional to the strength of current.

II. *When the same quantity of electricity is conveyed through different electrolytes, the masses of the different ions set free at the electrodes are proportional to their chemical equivalents.*

By "chemical equivalents" are meant the relative

quantities of the ions which are chemically equivalent to one another, or take part in equivalent chemical reactions. Thus, 32.5 gm. of zinc or 31.7 gm. of copper take the place of one gm. of hydrogen in sulphuric acid (H_2SO_4) to form zinc sulphate ($ZnSO_4$) or copper sulphate ($CuSO_4$), respectively.

The first law of electrolysis affords a valuable means of comparing the strength of two electric currents by determining the relative masses of any ion, such as silver or copper, deposited by the two currents in succession in the same time (§ 433).

426. Electroplating consists in covering bodies with a coating of any metal by means of the electric current. The process may be summarized as follows: Thoroughly clean the surface to remove all fatty matter. Attach the article to the negative electrode of a battery, and suspend it in a solution of some chemical salt of the metal to be deposited. If silver, cyanide of silver dissolved in cyanide of potassium is used; if copper, sulphate of copper. To maintain the strength of the solution a piece of the metal of the kind to be deposited is attached to the positive electrode of the battery. The action is similar to that heretofore given. Articles of iron, steel, zinc, tin, and lead cannot be silvered or gilded unless first covered with a thin coating of copper.

All silver plating, nickeling, gold plating, and so on, is done by this process.

427. Electrotyping consists in copying medals, woodcuts, type, and the like in metal, usually copper, by means of the electric current. A mold of the object is taken in wax or plaster of Paris. This is evenly covered with powdered graphite to make the surface a conductor, and

treated very much as an object to be plated. When the deposit has become sufficiently thick it is removed from the mold and backed or filled with type-metal.

Nearly all books nowadays are printed from electrotype plates, and not as formerly from movable types.

428. The Storage Cell. — Attach two lead plates, to which are soldered copper wires, to the opposite sides of a block of dry wood, and immerse them in dilute sulphuric acid, one part acid to five of water (Fig. 345). Connect this cell to a suitable battery B by means of key K_1; also to an ordinary electric house bell H through a key K_2 (Fig. 346). A galvanoscope G may be included in the circuit to show the direction of the current. Pass a current through the lead cell for a few minutes by closing the key K_1. Hydrogen bubbles will be disengaged from the cathode, while the anode will begin to turn dark brown. Next open the key K_1, thus disconnecting the battery B, and close key K_2. The bell will ring and the galvanoscope will indicate a discharge current in the opposite direction to the first or charging current. The bell will soon cease ringing, and the charging may be repeated by again closing key K_1 while K_2 is open.

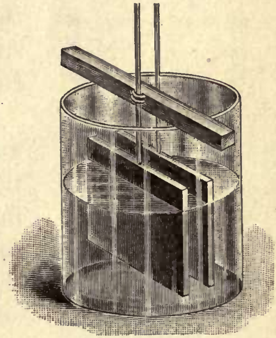


Fig. 345

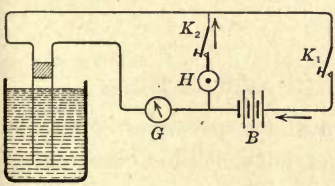


Fig. 346

The lead plates in an electrolyte of sulphuric acid illustrate a simple *lead storage cell.* The electrolysis of the sulphuric acid liberates oxygen at the anode, which combines with the lead electrode to form a chocolate-colored deposit of lead peroxide (PbO_2). Hydrogen accumulates on the cathode. When the charging battery is disconnected and the lead plates are joined by a conductor, a

current flows in the external circuit from the chocolate-colored plate, which is called the *positive electrode*, to the other one, called the *negative;* the lead peroxide is reduced to spongy lead on the positive plate, while some lead sulphate is formed on the negative. During subsequent charging this lead sulphate is reduced by the hydrogen to spongy lead. Note that the charging current passes through the storage cell in the opposite direction to the discharge current furnished by the cell itself.

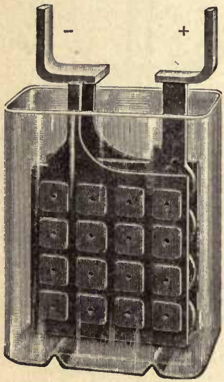


Fig. 347

The storage battery stores energy and not electricity. The energy of the charging current is converted into the potential energy of chemical separation in the storage cell. When the circuit of the charged secondary cell is closed, the potential chemical energy is reconverted into the energy of an electric current in precisely the same way as in a primary cell.

Fig. 347 shows a complete storage cell containing one positive and two negative plates.

III. OHM'S LAW AND ITS APPLICATIONS

429. Resistance. — Every conductor presents some obstruction to the passage of electricity. This obstruction is called its *electrical resistance*. The greater the conductance of a conductor the less its resistance, the one decreasing in the same ratio as the other increases. Resistance is the reciprocal of *conductance*. If R is the resistance of a conductor and C its conductance, then $R = \frac{1}{C}$.

430. Unit of Resistance. — The practical unit of resistance is the *ohm. It is represented by the resistance offered to an unvarying current by a thread of mercury at the temperature of melting ice, one square millimeter in cross sectional area, and of a length of* 106.3 *cm.* Mercury has been chosen because it can be obtained in great purity, and the cross section of the glass tube containing it can be measured with the highest degree of accuracy.

431. Laws of Resistance. — 1. *The resistance of a conductor is proportional to its length.* For example, if 39 ft. of No. 24 copper wire (B. & S. gauge) have a resistance of 1 ohm, then 78 ft. of the same wire will have a resistance of 2 ohms.

2. *The resistance of a conductor is inversely proportional to its cross sectional area.* In the case of round wire the resistance is proportional to the square of the diameter. For example, No. 24 copper wire has twice the diameter of No. 30. Then 39 ft. of No. 24 has a resistance of 1 ohm, and 9.75 ft. of No. 30 (one fourth of 39) also has a resistance of 1 ohm, both at 22° C.

3. *The resistance of a conductor of given length and cross section depends upon the material of which it is made, and is affected by anything which modifies its molecular condition.* For example, the resistance of 2.2 ft. of No. 24 German silver wire is 1 ohm, while it takes 39 ft. of copper wire of the same diameter to give the same resistance. Heat affects the molecular condition of a conductor, and consequently affects its resistance. Metal conductors have their resistance increased by a rise of temperature, but all are not affected to the same extent. The resistance of a copper conductor increases much more for a given rise of temperature than one of German silver;

other alloys, such as manganin, show very little change with temperature. The resistance of carbon and of electrolytes decreases with a rise of temperature. The resistance of a hot carbon filament in an incandescent lamp is only about half as great as when it is cold.

432. Formula for Resistance. — The above laws are conveniently expressed in the following formula for the resistance of a wire :

$$R = k\frac{l}{C.M.},$$

in which k is a constant depending on the material, l the length of the wire in feet, and $C.M.$ denotes "circular mils." A "mil" is a thousandth of an inch, and circular mils are the square of the mils; that is, the square of the diameter of the wire in thousandths of an inch. For example, if the diameter of a wire is 0.020 in., then in mils it is 20, and the circular mils (C.M.) will be the square of 20 or 400. Now if the length of a wire conductor is expressed in feet, and its cross section in circular mils, then it is easy to give to k for each kind of conductor such a value that R in the above formula will be in ohms.

The following are the values of k in ohms for several metals, at 20° C.:

Silver	9.53	Iron	61.3	German silver	181.3
Copper	10.19	Platinum	70.5	Mercury	574

433. Strength of Current. — The *strength* or *intensity* of a current is measured by the magnitude of the effects produced by it. Any such effect may be made the basis of a system of measurement. The quantity of an ion deposited in a second is a convenient one to use in defining unit strength of current. *The unit of current strength is the*

ampere. It is defined as the current which will deposit by electrolysis, under suitable conditions, 0.001118 gm. of silver per second. The ampere deposits 4.025 gm. of silver in one hour. A milliampere is a thousandth of an ampere. It is to be noted that the electrolytic method measures only the quantity of electricity passing through the decomposing cell, called a *voltameter*, in the given time.

434. Electromotive Force *is the cause of an electric flow.* It is often called *electric pressure* from its superficial analogy to water pressure. The unit of electromotive force (E.M.F.) is the *volt. A volt is the E.M.F. which will cause a current of one ampere to flow through a resistance of one ohm.* The E.M.F. of a voltaic cell depends upon the materials employed, and is entirely independent of the size and shape of the plates. The E.M.F. of a Daniell cell and of a gravity cell is about 1.1 volts; of a Leclanché and of a dry cell, 1.5 volts; of a lead storage cell, 2 volts.

The practical international standard of electromotive force is the Weston Normal Cell. The electrodes are cadmium amalgam for the negative and mercury for the positive. The electrolyte is a saturated solution of cadmium sulphate, and the depolarizer is mercurous sulphate (Fig. 348). The E.M.F. of the Weston cell in volts is given by the following equation, the temperature t being in centigrade degrees:

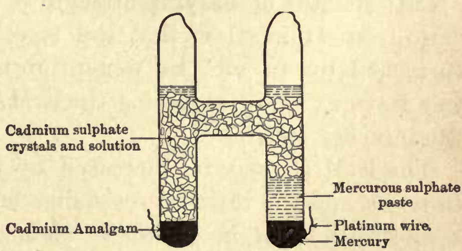


Fig. 348

$$E = 1.0183 - 0.00004\,(t - 20°). \quad \text{(Equation 35)}$$

435. Ohm's Law. — The definite relation existing between strength of current, resistance, and E.M.F. is known as *Ohm's Law:*

The strength of a current equals the electromotive force divided by the resistance; then

$$\textit{current in amperes} = \frac{\textit{E.M.F. (or potential difference) in volts}}{\textit{resistance in ohms}},$$

or in symbols, $I = \frac{E}{R}$, ... (Equation 36)

where I is the current in amperes, E the E.M.F. in volts, and R the resistance in ohms. Applied to a battery, if R is the resistance external to the cell, and r the internal resistance of the cell itself, then

$$I = \frac{E}{r + R}.$$

From equation (36), $E = IR$ and $R = \frac{E}{I}$.

436. Methods of Varying Strength of Current. — It is evident from Ohm's law that the strength of the current furnished by an electric generator may be increased in two ways: (1) by increasing the E.M.F.; (2) by reducing the internal resistance.

The E.M.F. may be increased by joining several cells *in series*, and the internal resistance may be diminished by connecting them *in parallel.* Enlarging the plates of a battery or bringing them closer together diminishes the internal resistance.

437. Connecting in Series. — To connect cells in series, join the positive electrode of one to the negative electrode of the next, and so on until all are connected. The elec-

trodes of the *battery* thus connected in series are the positive electrode of the last one in the series and the negative electrode of the first one (Fig. 349). Fig. 350 is the conventional sign for a single cell; Fig. 351 shows four cells in series.

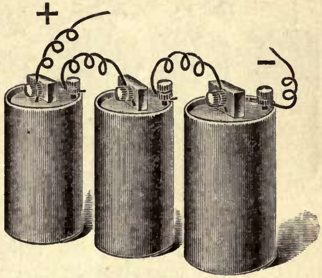


Fig. 349

When n similar cells are connected in series, the E. M. F. of the battery is n times that of a single cell; the resistance is also n times the resistance of one cell. Hence, by Ohm's law for n cells connected in series the current is

$$I = \frac{nE}{R + nr}.$$

To illustrate, if four cells, each having an E. M. F. of 2 volts and an internal resistance of 0.5 ohm, are joined

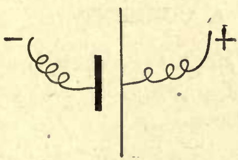


Fig. 350

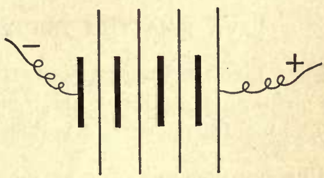


Fig. 351

in series with an external resistance of 10 ohms, the current will be

$$I = \frac{4 \times 2}{10 + 4 \times 0.5} = 0.67 \text{ ampere.}$$

438. Connecting in Parallel. — When all the positive terminals are connected together on one side and the

negative on the other, the cells are grouped in *parallel* (Fig. 352). With n similar cells the effect of such a grouping is to reduce the internal resistance to $\frac{1}{n}$th that of a single cell. It is equivalent to increasing the area of the plates n times. All the cells side by side contribute equal shares to the output of the battery. The E. M. F. of the group is the same as that of a single cell.

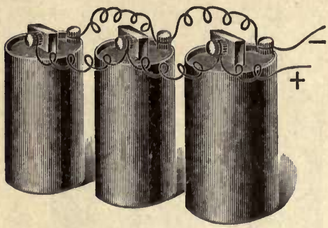


Fig. 352

Connection in parallel is used chiefly with storage cells, not for the purpose of reducing the internal resistance of the battery, but for the purpose of permitting a larger current to be drawn from it with safety to the cells. The ampere capacity of a storage cell depends on the area of the plates. If twenty amperes may be drawn from a single storage cell, then from two such cells in parallel forty amperes may be taken.

IV. HEATING EFFECTS OF A CURRENT

439. Electric Energy Converted into Heat. — Send an electric current through a piece of fine iron wire. The wire is heated, and it may be fused if the current is sufficiently strong.

The conversion of electrical energy into other forms is a familar fact. In the storage battery the energy of the charging current is converted into the energy of chemical separation and stored as the potential energy of the charged cells. In this experiment the energy of the current is transformed into heat because of the resistance which the wire offers. If the resistance of an electric circuit is not uniform, the most heat will be generated where the resistance is the greatest.

440. Joule's Law. — Joule demonstrated experimentally that the number of units of heat generated in a conductor by an electric current is proportional:

a. To the resistance of the conductor.

b. To the square of the strength of current.

c. To the length of time the current flows.[1]

441. Applications of Electric Heating. — Some of the more important applications of electric heating are the following:

1. *Electric Cautery.* A thin platinum wire heated to incandescence is employed in surgery instead of a knife. Platinum is very infusible and is not corrosive.

2. *Safety Fuses.* Advantage is taken of the low temperature of fusion of some alloys, in which lead is a constituent, for making safety fuses to open a circuit automatically whenever the current becomes excessive.

3. *Electric Heating.* Electric street cars are often heated by a current through suitable resistances. Similar devices for cooking are now articles of commerce. Small furnaces for fusing, vulcanizing, and enameling are now common in dentistry.

Large furnaces are employed for melting refractory substances, for the reduction of certain ores, and for chemical operations demanding a high temperature.

4. *Electric Welding.* If the abutting ends of two rods or bars are pressed together, while a large current passes through them, enough heat is generated at the junction, where the resistance is greatest, to soften and weld them together. Fig. 353 shows three welded joints as they came from the welder.

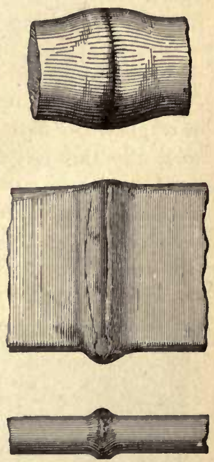


Fig. 353

[1] If H is the heat in calories, I the current strength in amperes, R the resistance in ohms, t the time in seconds, and 0.24 the number of calories equivalent to one joule, then the heat equivalent of a current is

$$H = 0.24 \times I^2Rt \text{ calories.}$$

V. MAGNETIC PROPERTIES OF A CURRENT

442. Magnetic Field Around a Conductor.— Dip a portion of a wire carrying a heavy current into fine iron filings. A thick cluster of them will adhere to the wire (Fig. 354); they will drop off as soon as the circuit is opened.

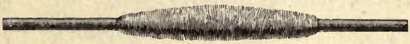


Fig. 354

The experiment shows that a conductor through which an electric current is passing has magnetic properties. The iron filings are magnetized by the current and set themselves at right angles to the wire. When the circuit is broken, they lose their magnetism and drop off.

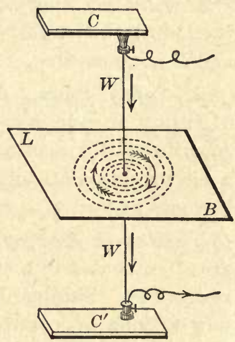


Fig. 355

443. Mapping the Magnetic Field. — Support horizontally a sheet of cardboard or of glass *LB* with a hole through it. Pass vertically through the hole a wire, *W*, connecting with a suitable electric generator, so that a strong current can be sent through the circuit (Fig. 355). Close the circuit and sift iron filings on the paper or glass about the wire, jarring the sheet by tapping it. The filings will arrange themselves in circular lines about the wire. Place a small mounted magnetic needle on the sheet near the wire; it will set itself tangent to the circular lines, and if the current is flowing downward, the north pole will point in the direction in which the hands of a watch move.

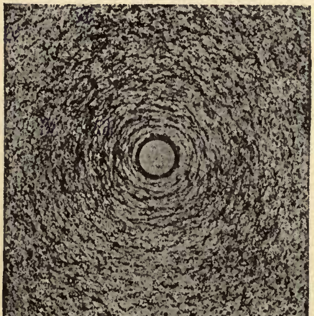


Fig. 356

The lines of magnetic force about a wire through which an electric current is flowing, are concentric circles. Fig.

356 was made from a photograph of these circular lines of force as shown by iron filings on a plate of glass. Their direction relative to the current is given by the following rule:

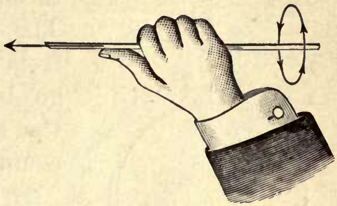


Fig. 357

Grasp the wire by the right hand so that the extended thumb points in the direction of the current; then the fingers wrapped around the wire indicate the direction of the lines of force (Fig. 357).

Fig. 358 is a sketch intended to show the direction of these circular lines of magnetic force (or magnetic whirl) which everywhere surround a wire conveying a current.

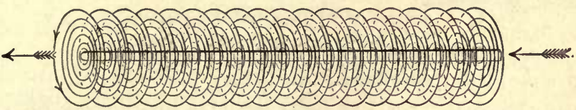


Fig. 358

444. Properties of a Circular Conductor. — Bend a copper wire into the form shown in Fig. 359, the diameter of the circle being about 20 cm. Suspend it by a long untwisted thread, so that the ends dip into the mercury cups shown in cross section in the lower part of the figure. Send a current through the suspended wire by connecting a battery to the binding posts. A bar magnet brought near the face of the circular conductor will cause the latter to turn about a vertical axis and take up a position with its plane at right angles to the axis of the magnet. With a strong current the circle will turn under the influence of the earth's magnetism.

This experiment shows that a circular current acts like a disk magnet, whose poles are its faces. The lines

of force surrounding the conductor in this form pass through the circle and around from one face to the other through the air outside the loop. The north-seeking side is the one from which the lines issue; and to an observer looking toward this side, the current flows around the loop counter-clockwise (Fig. 360).

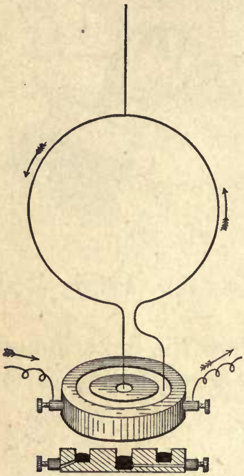


Fig. 359

If instead of a single turn we take a long insulated wire and coil it into a number of parallel circles close together, the magnetic effect will be increased. Such a coil is called a *helix* or *solenoid;* and the passage of an electric current through it gives to it all the properties of a cylindrical bar magnet.

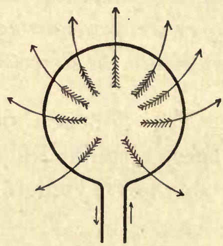


Fig. 360

445. Polarity of a Helix.— The polarity of a helix may be determined by the following rule:

Grasp the coil with the right hand so that the fingers point in the direction of the current; the north pole will then be in the direction of the extended thumb.

446. Mutual Action of Two Currents.— Make a rectangular coil of insulated copper wire by winding four or five layers around the edge of a board about 25 cm. square. Slip the wire off the board and tie the parts together in a number of places with thread. Bend the ends at right angles to the frame, remove the insulation,

and give them the shape shown in Fig. 361. Suspend the wire frame by a long thread so that the ends dip into the mercury cups.

Make a second similar but smaller coil and connect it in the same circuit with the rectangular coil and a battery.

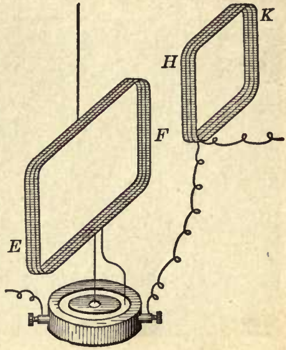


Fig. 361

First. Hold the coil *HK* with its plane perpendicular to the plane of the coil *EF*, with its edge *H* parallel to *F*, and with the currents in these two adjacent portions flowing in the same direction. The suspended coil will turn upon its axis, the edge *F* approaching *H*, as if it were attracted.

Second. Reverse *HK* so that the currents in the adjacent portions *K* and *F* flow in opposite directions. The edge *F* of the suspended coil will be repelled by *K*.

Third. Hold the coil *HK* within *EF*, so that their lower sides form an angle. *EF* will turn until the currents in its lower side are parallel with those in *H*, and flowing in the same direction.

These facts may be summarized in the following *laws of action between currents:*

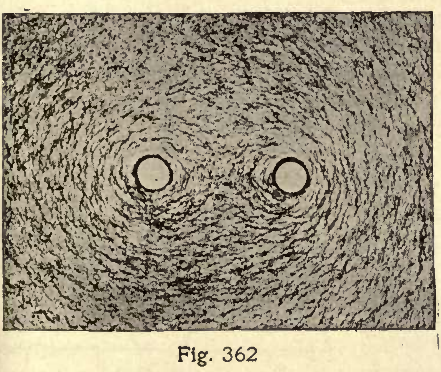


Fig. 362

I. *Parallel currents flowing in the same direction attract.*

II. *Parallel currents flowing in opposite directions repel.*

III. *Currents making an angle with each other tend to become parallel and to flow in the same direction.*

447. Magnetic Fields about Parallel Currents.—Fig. 362 was made from a photograph of the magnetic field about

two parallel currents in the same direction perpendicular to the figure. Many of these lines of force surround both wires, and it is the tension along them that draws the wires together.

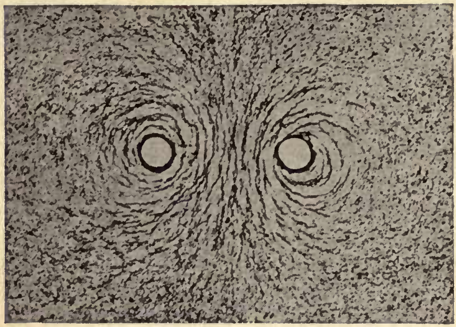


Fig. 363

Fig. 363 was made from a photograph of the field when the currents were in opposite directions. The lines of force are crowded together between the wires, and their reaction in their effort to recover their normal position forces the wires apart.

VI. ELECTROMAGNETS

448. Effect of Introducing Iron into a Solenoid. — Wind evenly on a paper tube, about 2 cm. in diameter and 15 cm. long, three layers of No. 18 insulated copper wire. Support the tube and wire in a slot cut in a sheet of cardboard. Pass an electric current through the solenoid and note the magnetic field as mapped out by iron filings (Fig. 364). Repeat after filling the tube with straight soft iron wires. The magnetic field will be greatly strengthened by the iron.

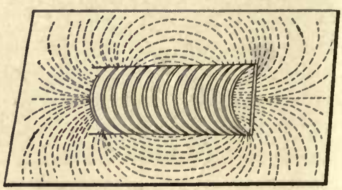


Fig. 364

A helix of wire about an iron core is an *electromagnet*. It was first made by Sturgeon in 1825. The presence of the iron core greatly increases the number of lines of force threading through the helix from end to end, by reason of

the greater permeability of iron as compared with air (Fig. 365). If the iron is omitted, there are not only fewer lines of force, but because of their leakage at the sides of the helix, fewer traverse the entire length of the coil.

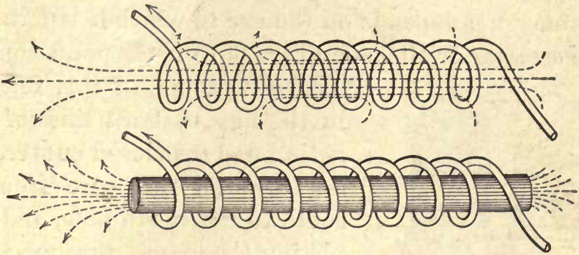


Fig. 365

The soft iron core of an electromagnet does not show much magnetism except while the current is flowing through the magnetizing coil. The loss of magnetism is not quite complete when the current is interrupted; the small amount remaining is called *residual magnetism.*

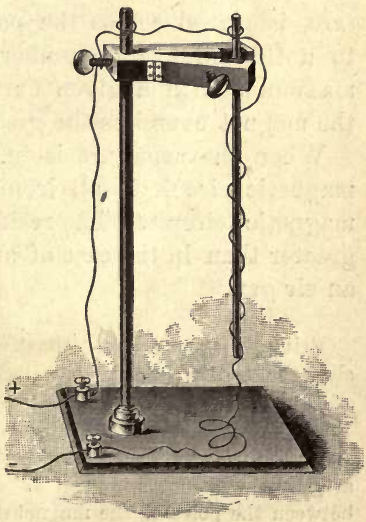


Fig. 366

449. Relation between a Magnet and a Flexible Conductor. — Iron filings arranged in circles about a conductor may be regarded as flexible magnetized iron winding itself into a helix around the current; conversely, a flexible conductor, carrying a current, winds itself around a straight bar magnet. The flexible conductor of Fig. 366 may be made of tinsel cord or braid. Directly the circuit

is closed, the conductor winds slowly around the vertical magnet; if the current is then reversed, the conductor unwinds and winds up again in the reverse direction.

450. The Horseshoe Magnet. — The form given to an electromagnet depends on the use to which it is to be put. The *horseshoe* or U-shape (Fig. 367) is the most common.

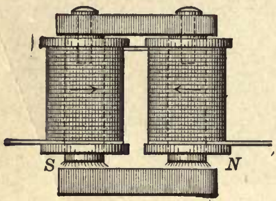


Fig. 367

The advantage of this form lies in the fact that all lines of magnetic force are closed curves, passing through the core from the south to the north pole, and completing the circuit through the air from the north pole back to the south pole. The U-shape lessens the distance through the air and thus increases the number of lines. Moreover, when an iron bar, called the *armature*, is placed across the poles, the air gap is reduced to a thin film, the number of lines is increased to a maximum with a given current through the helix, and the magnet exercises the greatest pull on the armature.

When the armature is in contact with the poles, the magnetic circuit is all iron, and is said to be a *closed* magnetic circuit. The residual magnetism is then much greater than in the case of an open magnetic circuit with an air gap.

Bring the armature in contact with the iron poles of the core, and close the electric circuit; after the circuit is opened, the armature will still cling to the poles and can be removed only with some effort. Then place a piece of thin paper between the poles and the armature. After the magnet has again been excited and the circuit opened, the armature will not now "stick." The paper makes a thin air gap between the poles of the magnet and the armature, and thus reduces the residual magnetism.

451. Applications of Electromagnets. — The uses to which electromagnets are put in the applications of electricity are so numerous that a mere reference to them must suffice. The electromagnet enters into the construction of electric bells, telegraph and telephone instruments, dynamos, motors, signaling devices, etc. It is also extensively used in lifting large masses of iron, such as castings, rolled plates, pig iron, and steel girders (Fig. 368). The lifting power depends chiefly on the cross section of the iron core and on the *ampere turns;* that is, on the product of the number of amperes of current and the number of turns of wire wound on the magnet.

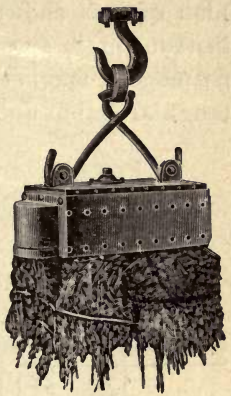


Fig. 368

VII. MEASURING INSTRUMENTS

452. The Galvanometer. — The instrument for the comparison of currents by means of their magnetic effects is called a *galvanometer.* A galvanoscope (§ 413) becomes a galvanometer by providing it with a scale so that the deflections may be measured. If the galvanometer is calibrated, so as to read directly in amperes, it is called an *ammeter.* In very sensitive instruments a small mirror is attached to the movable part of the instrument; it is then called a *mirror galvanometer.* Sometimes a beam of light from a lamp is reflected from this small mirror back to a scale, and sometimes the light from a scale is reflected back to a small telescope, by means of which the deflections are read. In either case the beam of light then becomes a long pointer without weight.

453. The d'Arsonval Galvanometer. — One of the most useful forms of galvanometer is the d'Arsonval. The

plan of it is shown in Fig. 369 and a complete working instrument in Fig. 370. Between the poles of a strong permanent magnet of the horseshoe form swings a rectangular coil of fine wire in such a way that the current is led into the coil by the fine suspending wire, and out by the wire spiral running to the base. A small mirror is attached to the coil to reflect light from a lamp or an illuminated scale. Sometimes the coil carries a light aluminum pointer, which traverses a scale. Inside the coil is a soft iron tube supported from the back of the case. It is designed to concentrate the lines of force in the narrow openings between it and the poles of the magnet.

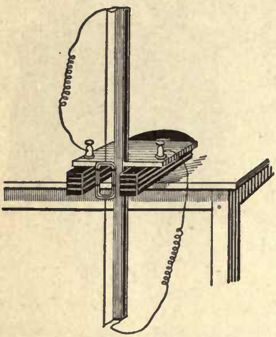


Fig. 369

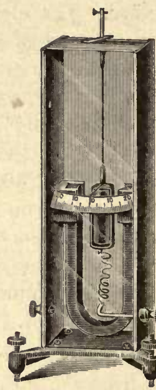


Fig. 370

In the d'Arsonval galvanometer the coil is movable and the magnet is fixed. Its chief advantages are simplicity of construction, comparative independence of the earth's magnetic field, and the quickness with which the coil comes to rest after deflection by a current through it.

454. The Voltmeter. — The *voltmeter* is an instrument designed to measure the difference of potential in volts. For direct currents the most convenient portable voltmeter is made on the principle of the d'Arsonval galvanometer. The appearance of one of the best-known

instruments of this class is shown in Fig. 371. The interior is represented by Fig. 372, where a portion of the instrument is cut away to show the coil and the springs. The current is led in by one spiral spring and out by the other. Attached to the coil is a very light aluminum pointer, which moves over the scale seen in Fig. 371, where it stands at zero. Soft iron polepieces are screwed fast to the poles of the permanent magnet, and they are so shaped that the divisions of the scale in volts are equal.

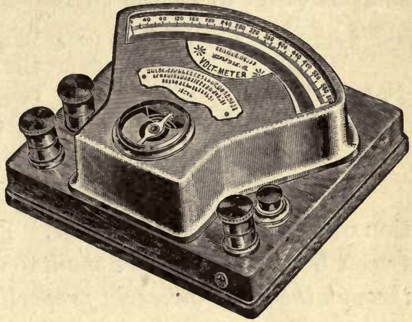


Fig. 371

In circuit with the coil of the instrument is a coil of wire of high resistance, so that when the voltmeter is placed in circuit, only a small current will flow through it.

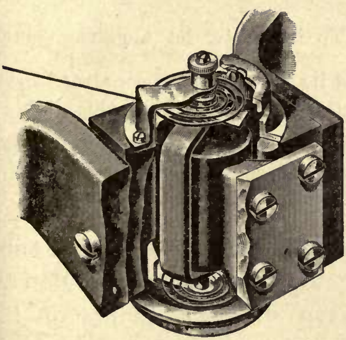


Fig. 372

455. The Ammeter, designed to measure electric currents in amperes, is very similar in construction to the voltmeter. Its coil has only a few turns of wire and its resistance is low, so that when the ammeter is placed in circuit, it will not change the value of the current to be measured.

456. Divided Circuits — Shunts. — When the wire leading from any electric generator is divided into two branches, as at B (Fig. 373), the current also divides, part flowing by one path and part by the other. The sum of these two currents is always equal to the current in the undivided part of the circuit, since there is no accumulation of electricity at any point. Either of the branches between B and A is called a *shunt* to the other, and *the currents through them are inversely proportional to their resistances.*

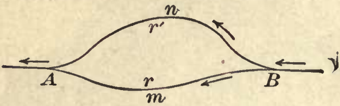


Fig. 373

457. Resistance of a Divided Circuit. — Let the total resistance between the points A and B (Fig. 373) be represented by R, that of the branch BmA by r, and of BnA by $r.'$ The conductance of BA equals the sum of the conductances of the two branches; and, as conductance is the reciprocal of resistance, the conductances of BA, BmA, and BnA are $\frac{1}{R}$, $\frac{1}{r}$, and $\frac{1}{r'}$ respectively; then $\frac{1}{R} = \frac{1}{r} + \frac{1}{r'}$. From this we derive $R = \frac{rr'}{r + r'}$. To illustrate, let a galvanometer whose resistance is 100 ohms have its binding posts connected by a shunt of 50 ohms resistance; then the total resistance of this divided circuit is $\frac{100 \times 50}{100 + 50} = 33^1$ ohms. The introduction of a shunt always lessens the resistance between the points connected.

458. Loss of Potential along a Conductor. — When a current flows through a conductor a difference of potential exists, in general, between different points on it. Let A, B, C be three points on a conductor conveying a current, and let there be *no source of E. M. F. between these points.* Then if the current flows from A to B, the potential at A is higher than at B, and the potential at B is higher than at C. If the potential difference

between A and B and that between B and C be measured, the ratio of the two will be the same as the ratio of the resistances between the same points. This is only another statement of Ohm's law. For since $I = \frac{E}{R}$, and the current is the same through the two adjacent sections of the conductor, the ratio of the potential differences to the resistances of the two sections is the same. This important principle, of which great use is made in electrical measurements, may be expressed by saying that, when the current is constant, *the loss of potential along a conductor is proportional to the resistance passed over.*

459. Wheatstone's Bridge. — The Wheatstone's Bridge is a device for measuring resistances. The four conductors R_1, R_2, R_3, R_4 are the *arms* and BD the *bridge* (Fig. 374). When the circuit is closed by closing the key K_2, the current divides at A, the two parts reuniting at C. The loss of potential along ABC is the same as along ADC. If no current flows through the galvanometer G when the key K_1 is also closed, then there is no potential difference between B and D to produce a current. Under these conditions the loss of potential from A to B is the same as from A to D. We may then get an expression for these potential differences and place them equal to each other.

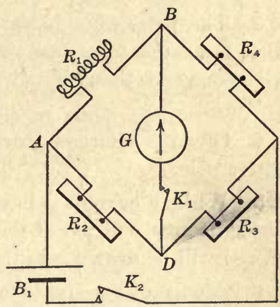


Fig. 374

Let I_1 be the current through R_1; it will also be the current through R_4, because none flows across through the galvanometer. Also let I_2 be the current through the branch ADC. Then the potential difference between A and B by Ohm's law (§ 435) is equal to R_1I_1; and the equal potential difference between A and D is R_2I_2. Equating these expressions,

$$R_1I_1 = R_2I_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (a)$$

In the same way the equal potential differences between B and C

and D and C give $R_4 I_1 = R_3 I_2$ . . . . (b)
Dividing (a) by (b) gives

$$\frac{R_1}{R_4} = \frac{R_2}{R_3} \quad \text{. . . . . . (Equation 37)}$$

In practice three of the four resistances are adjustable and of known value. They are adjusted until the galvanometer shows no deflection when the key K_1 is closed after key K_2. The value of the fourth resistance is then derived from the relation in equation (37).

Questions and Problems

1. An electric bell wire passes through a room and the battery is inaccessible. How may one determine the direction of the current through the wire?

2. How can it be proved that the strength of current is the same in all portions of an undivided circuit?

3. The poles of a battery are joined by a thin platinum wire, which is heated to a dull red. If a piece of ice is applied to the wire at one end, the remainder of the wire will glow more brightly. Explain.

4. Given a charged storage battery. Determine which is the positive pole.

5. While a current is passing through a helix, a small iron rod is brought near one end of the helix and in line with its axis. The iron rod will be drawn into the helix. Explain.

6. A current passing through a long elastic spiral of wire causes it to shorten. Explain.

7. Calculate the resistance of 100 ft. of copper wire ($k = 10.19$) No. 24 (diam. = 0.0201 in.).

8. No. 20 wire has a diameter of 0.032 in. How many feet of German silver wire ($k = 181.3$) will it take to make a 20-ohm coil?

9. How many feet of iron wire ($k = 61.3$), No. 10 (diam. = 0.1014 in), will it take to make a coil of 50 ohms resistance?

10. A current of one ampere deposits by electrolysis 1.1833 gm. of copper in an hour. How many amperes in 10 hours will deposit 1 kgm. of copper?

11. A current of 0.5 ampere is passed through a solution of silver nitrate for 30 min. How much silver is deposited?

12. What strength of current in amperes will deposit 10 gm. of silver by electrolysis in an hour?

13. What current will a battery having an E. M. F. of 2.2 volts and an internal resistance of 0.2 ohm supply through an external resistance of 5 ohms?

14. How large a current will a battery of 6 cells (E. M. F., 1.5 volts each) connected in series send through an external resistance of 6 ohms, the internal resistance of each cell being 0.5?

15. If a dry cell has an E. M. F. of 1.5 volts and sends a current of 20 amperes through an ammeter (resistance negligible), what is the internal resistance of the cell?

16. What current will be derived from a Daniell cell, E. M. F. 1.1 volts, internal resistance 1 ohm, in series with a dry cell, E. M. F. 1.5 volts, internal resistance 0.2 ohm, when the external resistance is 4 ohms?

17. A current of 10 amperes passes through a resistance of 1 ohm for half an hour. How many calories of heat are generated?

18. A current of 2.1 amperes is sent through a divided circuit of two branches, with resistances of 5 and 10 ohms respectively. Calculate the current in each branch.

19. If the current through an incandescent lamp is 0.55 ampere and the potential difference between its terminals 110 volts, what is the resistance of the lamp?

20. What resistance would be necessary in circuit with an electric lamp when the potential difference between its terminals is 50 volts, the pressure in the main line 200 volts, and the current through the lamp 12 amperes?

CHAPTER XIII

ELECTROMAGNETIC INDUCTION

I. FARADAY'S DISCOVERIES

460. Electromotive Force Induced by a Magnet. — Wind a number of turns of fine insulated wire around the armature of a horse-shoe magnet, leaving the ends of the iron free to come in contact with the poles of the permanent magnet. Connect the ends of the coil to a sensitive galvanometer, the armature being in contact with the magnetic poles, as shown in Fig. 375. Keeping the magnet fixed, suddenly pull off the armature. The galvanometer will show a momentary current. Suddenly bring the armature up to the poles of the magnet; another momentary current in the reverse direction will flow through the circuit.

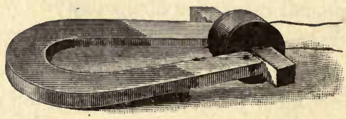


Fig. 375

Fig. 376

Connect a coil of insulated wire, consisting of a large number of turns, in circuit with a d'Arsonval galvanometer (Fig. 376). Thrust quickly into the coil the north pole of a bar magnet. The galvanometer will show a transient current, which will flow only during the motion of the magnet. When the magnet is suddenly withdrawn a transient current is produced in the opposite direction to the first one. If the south pole be thrust into

the coil, and then withdrawn, the currents in both cases are the reverse of those with the north pole. If we substitute a helix of a smaller number of turns, or a weaker bar magnet, the deflection will be less.

The momentary electromotive forces generated in the coil are known as *induced electromotive forces*, and the currents as *induced currents.* They were discovered by Faraday in 1831.

461. Laws of Electromagnetic Induction.— When the armature in the first experiment of the last article is in contact with the poles of the magnet, the number of lines of force passing through the coil, or linked with it, is a maximum. When the armature is pulled away, the number of magnetic lines threading through the coil rapidly diminishes.

When the magnet in the second experiment is thrust into the coil, it carries its lines of force with it, so that some of them at least encircle, or are linked with, the wires of the coil. In both experiments an electromotive force is generated only while the number of lines so linked with the coil is changing. The E. M. F. is generated in the coil in accordance with the following laws:

I. *An increase in the number of lines of force threading through a coil produces an indirect electromotive force; a decrease in the number of lines produces a direct electromotive force.*

II. *The electromotive force induced is proportional to the rate of change in the number of lines of force threading through the coil.*

These two laws give the direction and value of induced electromotive forces. A *direct* E. M. F. has a *clockwise* direction to an observer looking along the lines of force of the magnet; an *indirect* E. M. F. is one in the opposite

direction. Thus, in Fig. 377 the north pole of the magnet is moving into the coil in the direction of the arrow; there is an *increase* in the number of lines passing through the coil, and the E. M. F. and current are *indirect* or opposite watch hands, as shown by the arrows on the coil, to an observer looking at the coil in the direction of the arrow on the magnet.

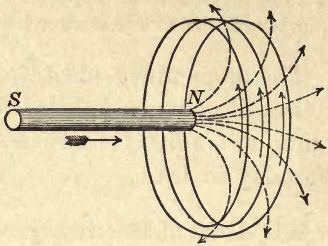


Fig. 377

462. Induction by Currents. — Connect the coil of Fig. 376 to a d'Arsonval galvanometer, and a second smaller coil to the terminals of a battery (Fig. 378). If the current through P is kept constant, when P is made to approach S an E. M. F. is generated in S tending to send a current in a direction opposite to the current around P; removing the coil P generates an opposite E. M. F. These E. M. F.'s act in S only so long as P is moving.

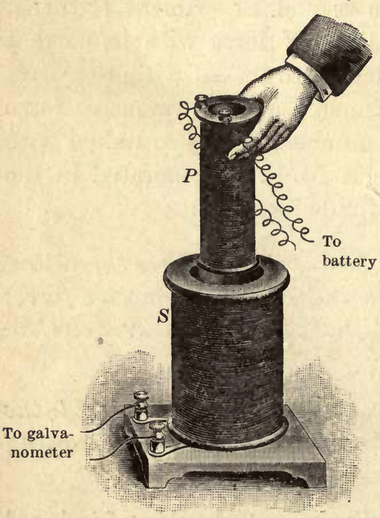


Fig. 378

Next insert the coil P in S with the battery circuit open. If then the battery circuit is closed, the needle of the galvanometer will be deflected, but will shortly come again to rest at zero. The direction of this momentary current is opposite to that in P. Opening the battery circuit produces another momentary current through S but in the opposite direction. Increasing and decreasing the current through P has the same effect as closing and opening the circuit.

If while P is inside S with the battery circuit closed, a bar of soft iron is placed within P, there is an increase of magnetic lines through both coils and the inductive effect in S is the same as that produced by closing the circuit through P.

The coil P is called the *primary* and S the *secondary* coil. The results may be summarized as follows:

I. *Momentary indirect electromotive forces are induced in the secondary by the approach, the starting, or the strengthening of a current in the primary coil.*

II. *Momentary direct electromotive forces are induced in the secondary by the receding, the stopping, or the weakening of a current in the primary coil.*

The primary coil becomes a magnet when carrying an electric current (§ 444) and acts toward the secondary coil as if it were a magnet. The soft iron increases the magnetic flux through the coil and so increases the induction.

463. Lenz's Law. — When the north pole of the magnet is thrust into the coil of Fig. 377, the induced current flowing in the direction of the arrows produces lines of force running in the opposite direction to those from the magnet (§ 443). These lines of force tend to oppose the change in the magnetic field within the coil, or the magnetic field set up by the coil opposes the motion of the magnet.

Again, when the primary coil of Fig. 378 is inserted into the secondary, the induced current in the latter is opposite in direction to the primary current, and parallel currents in opposite directions repel each other. In every case of electromagnetic induction the change in the magnetic field which produces the induced current is always opposed by the magnetic field due to the induced current itself.

The law of Lenz respecting the direction of the induced current is broadly as follows:

The direction of an induced current is always such that it produces a magnetic field opposing the motion or change which induces the current.

II. SELF-INDUCTION

464. Joseph Henry's Discovery. — Joseph Henry discovered that a current through a helix with parallel turns acts inductively on its own circuit, producing what is often called the *extra current*, and a bright spark across the gap when the circuit is opened. The effects are not very marked unless the helix contains a soft iron core.

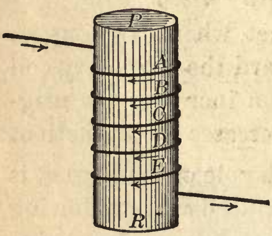


Fig. 379

Let a coil of wire be wound around a wooden cylinder (Fig. 379). When a current is flowing through this coil, some of the lines of force around one turn, as *A*, thread through adjacent turns; if the cylinder is iron, the number of lines threading through adjacent turns will be largely increased on account of the superior permeability of the iron (§ 365). Hence, at the make of the circuit, the production of magnetic lines threading through the parallel turns of wire induces a counter-E. M. F. opposing the current. The result is that the current does not reach at once the value given by Ohm's law. At the break of the circuit, the induction on the other hand produces a direct E. M. F. tending to prolong the current. With many turns of wire, this direct E. M. F. is high enough to break over a short gap and produce a spark.

465. Illustrations of Self-Induction. — Connect two or three cells in series. Join electrically a flat file to one pole and a piece of iron wire to the other. Draw the end of the wire lengthwise along the

Joseph Henry (1797–1878) was born at Albany, New York. The reading of Gregory's Lectures on Experimental Philosophy interested him so greatly in science that he began experimenting. In 1829 he constructed his first electromagnet. In 1832 he was appointed professor of natural philosophy at Princeton College. In 1846 he became secretary of the Smithsonian Institution in Washington. It is almost certain that he anticipated Faraday's great discovery of magneto-electric induction by a whole year but failed to announce it. His principal investigations were in electricity and magnetism, and chiefly in the realm of induced currents.

file; some sparks will be visible, but they emit little light. Now put an electromagnet in the circuit to increase the self-induction; the sparks are now much longer and brighter.

Connect as shown in Fig. 380 a large electromagnet *M*, a storage battery *B*, a circuit breaker *K*, and an incandescent lamp *L* of such a size that the battery alone will light it to nearly its full candle power. The circuit divides between the lamp and the electromagnet, and since the latter is of low resistance, when the current reaches its steady state most of it will go through the coils of the magnet, leaving the lamp at only a dull red. At the instant when the circuit is closed, the self-induction of the magnet acts against the current and sends most of it around through the lamp. It accordingly lights up at first, but quickly grows dim as the current rises to its steady value in *M*.

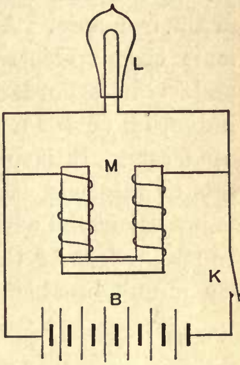


Fig. 380

Now open the circuit breaker *K*, cutting off the battery. The only closed circuit is now the one through the magnet and the lamp; but the energy stored in the magnetic field of the electromagnet is then converted into electric energy by means of self-induction, and the lamp again lights up brightly for a moment.

III. THE INDUCTION COIL

466. Structure of an Induction Coil. — The *induction coil* is commonly used to give transient flashes of high electromotive force in rapid succession. A primary coil of comparatively few turns of stout wire is wound around an iron core, consisting of a bundle of iron wires to avoid induced or eddy currents in the metal of the core; outside of this, and

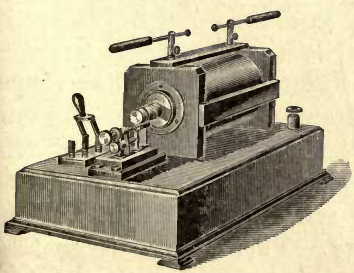


Fig. 381

carefully insulated from it, is the secondary of a very large number of turns of fine wire. The inner or primary coil is connected to a battery through a circuit breaker (Fig. 381). This is an automatic device for opening and closing the primary circuit and is actuated by the magnetism of the iron core. At the "make" and "break" of the primary circuit electromotive forces are induced in the secondary in accordance with the laws of electromagnetic induction (§ 461). Large induction coils include also a *condenser.* It is placed in the base and consists of two sets of interlaid layers of tin foil, separated by sheets of paper saturated with paraffin. The two sets are connected to two points of the primary circuit on opposite sides of the circuit breaker (Fig. 382).

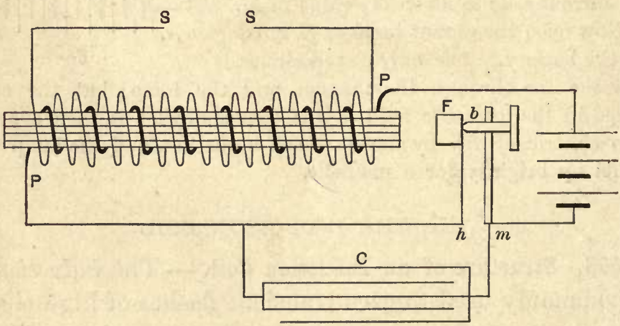


Fig. 382

467. Action of the Coil. — Figure 382 shows the arrangement of the various parts of an induction coil. The current first passes through the heavy primary wire *PP*, thence through the spring *h*, which carries the soft iron block *F*, then across to the screw *b*, and so back to the negative pole of the battery. This current magnetizes the iron core of the coil, and the core attracts the soft iron

block *F*, thus breaking the circuit at the point of the screw *b*. The core is then demagnetized, and the release of *F* again closes the circuit. Electromotive forces are thus induced in the secondary coil *SS*, both at the make and the break of the primary. The high E.M.F. of the secondary is due to the large number of turns of wire in it and to the influence of the iron core in increasing the number of lines of force which pass through the entire coil.

The self-induction of the primary has a very important bearing on the action of the coil. At the instant the circuit is closed, the counter E. M. F. opposes the battery current, and prolongs the time of reaching its greatest strength. Consequently the E. M. F. of the secondary coil will be diminished by self-induction in the primary. The E. M. F. of self-induction at the "break" of the primary is direct, and this added to the E. M. F. of the battery produces a spark at the break points of the circuit breaker.

468. Action of the Condenser. — The addition of a condenser increases the E. M. F. of the secondary coil in two ways: 1. It gives such an increase of capacity to the primary coil that at the moment of breaking the circuit the potential difference between the contact points does not rise high enough to cause a spark discharge across the air gap. The interruption of the primary is therefore more abrupt, and the E. M. F. of the secondary is increased. 2. After the break, the condenser *C*, which has been charged by the E. M. F. of self-induction, discharges back through the primary coil and the battery. The condenser causes an electric recoil in the current, and returns the stored charge as a current in the reverse direction through the primary, thus demagnetizing the core, in-

creasing the rate of change of magnetic flux, and increasing the induced E. M. F. in the secondary. The condenser momentarily stores the energy represented by the spark when no condenser is used, and then returns it to the primary and by mutual induction to the secondary, as indicated by the longer spark or the greater current. When the secondary terminals are separated, the discharge is all in one direction and occurs when the primary current is broken.

469. Experiments with the Induction Coil. — 1. *Physiological Effects.* — Hold in the hands the electrodes of a very small induction coil, of the style used by physicians. When the coil is working, a peculiar muscular contraction is produced.

The "shock" from large coils is dangerous on account of the high E. M. F. The danger decreases with the increase in the rapidity of the impulses or alternations. Experiments with induction coils, worked by alternating currents of very high frequency, have demonstrated that the discharge of the secondary may be taken through the body without injury.

2. *Mechanical Effects.* — Hold a piece of cardboard between the electrodes of an induction coil giving a spark 3 cm. long. The card will be perforated, leaving a burr on each side. Thin plates of any nonconductor can be perforated in the same manner.

3. *Chemical Effects.* — Place on a plate of glass a strip of white blotting-paper moistened with a solution of potassium iodide (a compound of potassium and iodine) and starch paste. Attach one of the electrodes of a small induction coil to the margin of the paper. Handle a wire leading to the other electrode with an insulator, and trace characters with the wire on the paper when the coil is in action. The discharge decomposes the potassium iodide, as shown by the blue mark. This blue mark is due to the action of the iodine on the starch.

If the current from the secondary of an induction coil be passed through air in a sealed tube, the nitrogen and oxygen will combine to

form nitrous acid. This is the basis of some of the commercial methods of manufacturing nitrogen compounds from the nitrogen of the air.

4. *Heating Effects.* — Fig. 383 shows the plan of the "electric bomb." It is usually made of wood. Fill the hole with gun powder as far up as the brass rods and close the mouth with a wooden ball. Connect the rods to the poles of the induction coil. The sparks will ignite the powder and the ball will be projected across the room.

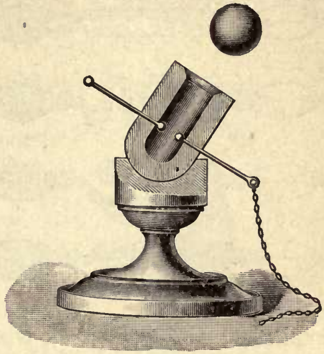


Fig. 383

The heating effect of the current in the secondary of a large induction coil may be shown by stretching between its poles a very thin iron wire. It will melt and burn vividly. If there is a small break in the wire, the discharge will melt the part connected to the negative pole of the coil, while the other part will remain below the temperature of ignition.

470. Discharges in Partial Vacua. — Place a vase of uranium on the table of the air pump, under a bell jar provided with a brass sliding rod passing air-tight through the cap at the top (Fig. 384). Connect the rod and the air pump table to the terminals of the induction coil. When the air is exhausted a beautiful play of light will fill the bell jar. The display will be more beautiful if the vase is lined part way up with tin-foil. This experiment is known as *Gassiot's cascade.* The experiment may be varied by admitting other gases and exhausting again. The aspect of the colored light will be entirely changed.

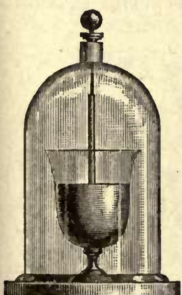


Fig. 384

The best effects are obtained with discharges from the secondary of an induction coil in glass tubes when the exhaustion is carried to a pressure of about 2 mm. of mercury, and the tubes are permanently

sealed. Platinum electrodes are melted into the glass at the two ends. Such tubes are known as *Geissler tubes.*

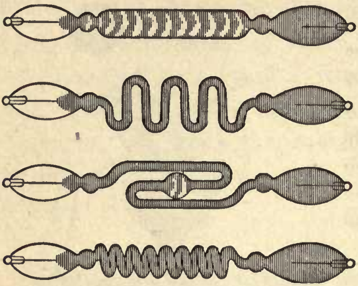


Fig. 385

They are made in a great variety of forms (Fig. 385), and the luminous effects are more intense in the narrow connecting tubes than in the large bulbs at the ends. The colors are determined by the nature of the residual gas. Hydrogen glows with a brilliant crimson; the vapor of water gives the same color, indicating that the vapor is dissociated by the discharge. An examination of this glow by the spectroscope gives the characteristic lines of the gas in the tube.

Geissler tubes often exhibit *stratifications*, which consist of portions of greater brightness separated by darker intervals. Stratifications have been produced throughout a tube 50 feet long. These stratifications or striæ present an unstable flickering motion, resembling that sometimes observed during auroral displays.

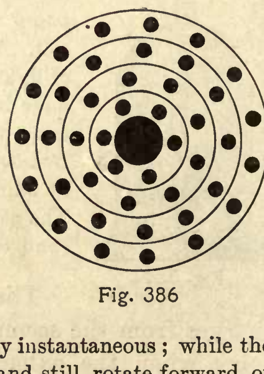


Fig. 386

471. The Discharge Intermittent. — On a disk of white cardboard about 20 cm. in diameter paste disks of black paper 2 cm. in diameter (Fig. 386). Rotate the disk rapidly by means of a whirling table or an electric motor and illuminate it by a Geissler tube in a dark room. The black spots will be sharp in outline because each flash is nearly instantaneous; while the spots in the different circles will either stand still, rotate forward, or rotate backward. If in the brief interval between the flashes the

disk rotates through an angle equal to that between the spots in one of the circles, the spots will appear to stand still; if it rotates through a slightly greater angle, the spots will appear to move slowly forward; if through a smaller angle, they will appear to move slowly backward.

Mount a Geissler tube on a frame attached to the axle of a small electric motor (Fig. 387). Illuminate the tube by an induction coil while it rotates. Star-shaped figures will be seen, consisting of a number of images of the tube, the number depending on the speed of the motor as compared with the period of vibration of the circuit breaker.

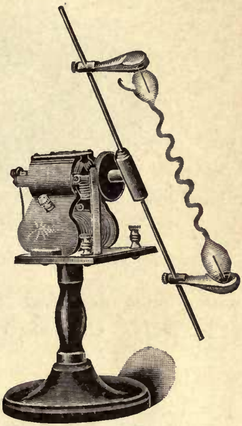


Fig. 387

472. Cathode Rays. — When the gas pressure in a tube is reduced below about a millionth of an atmosphere, the character of the discharge is much altered. The positive column of light extending out from the anode gradually disappears, and the sides of the tube glow with brilliant phosphorescence. With English glass the glow is blue; with German glass it is a soft emerald. The luminosity of the glass is produced by a radiation in straight lines from the *cathode* of the tube; this radiation is known as *cathode rays*. They were first studied by Sir William Crookes, and the tubes for the purpose are called *Crookes tubes*.

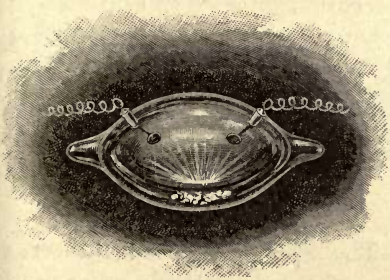


Fig. 388

Many other substances besides glass are caused to glow by the impact of cathode rays (Fig. 388), such as ruby,

diamond, and various sulphides. The color of the glow depends on the substance.

Cathode rays, unlike rays of light, are deflected by a magnet, and

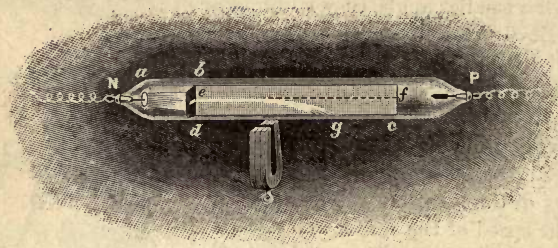


Fig. 389

when once deflected they do not regain their former direction (Fig. 389). Cathode rays proceed in straight lines, except as they are deflected by a magnet or by mutual repulsion. A screen placed across their path interrupts them and casts a shadow on the walls of the tube.

When the cathode is made in the form of a concave cup, the rays are brought to a focus at its center of curvature; platinum foil placed at this focus is raised to bright incandescence and may be fused (Fig. 390). Glass on which an energetic cathode stream falls may be heated to the point of fusion.

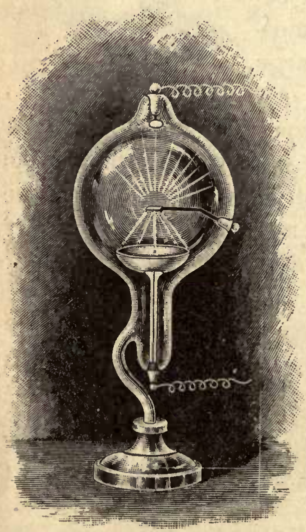


Fig. 390

It has been conclusively shown that cathode rays carry negative charges of electricity. Hence the mutual repulsion exerted on each other by two parallel cathode streams.

473. Roentgen Rays. — The rays of radiant matter, as Crookes called it, emanating from the cathode, give rise to

Sir William Crookes, a distinguished English chemist, was born in 1832. In 1873 he began a series of investigations on the properties of high vacua. While engaged in this work he invented the radiometer, developed the Crookes tubes, and discovered what he called "radiant matter." His investigations led him very close to the discoveries of Röntgen. He has edited the Quarterly Journal of Science since 1864.

Wilhelm Konrad Röntgen was born in 1845. It was at Würzburg, Germany, in 1895, that he discovered while passing electric charges through a Crookes tube, that a certain kind of radiation was emitted capable of passing through many substances known to be opaque to light. The nature of these rays being unknown, he called them "X-rays." They differ from the cathode rays discovered by Crookes, in that they affect a sensitized photographic plate.

another kind of rays when they strike the walls of the tube, or a piece of platinum placed in their path. These last rays, to which Roentgen, their discoverer, gave the name of "*X-rays*," can pass through glass, and so get out of the tube. They also pass through wood, paper, flesh, and many other substances opaque to light. They are stopped by bones, metals (except in very thin sheets), and by some other substances. Roentgen discovered that they affect a photographic plate like light. Hence, photographs can be taken of objects which are entirely invisible to the eye, such as the bones in a living body, or bullets embedded in the flesh.

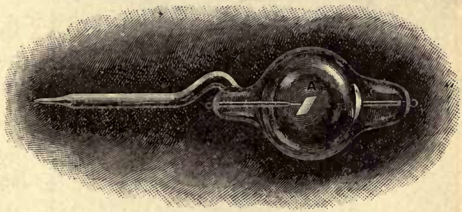


Fig. 391

A Crookes tube adapted to the production of Roentgen rays (Fig. 391) has a concave cathode *K*, and at its focus an inclined piece of platinum *A*, which serves as the anode. The X-rays originate at *A* and issue from the side of the tube.

474. X-Ray Pictures. — The penetrating power of Roentgen rays depends largely on the pressure within the tube. With high exhaustion the rays have high penetrating power and are then known as "hard rays." Hard rays can readily penetrate several centimeters of wood, and even a few millimeters of lead. With somewhat lower exhaustion, the rays are less penetrating and are then known as "soft rays."

The possibility of X-ray photographs depends on the variation in the penetrability of different substances for X-rays. Thus, the bones of the body absorb Roentgen rays more than the flesh, or are less penetrable by them. Hence fewer rays traverse them. Since Roentgen rays cannot be focused, all photographs taken by them are only shadow

Fig. 392

pictures. A Roentgen photograph of a gloved hand is shown in Fig. 392. The ring on the little finger, the two glove buttons, and the cuff studs are conspicuous. The flesh is scarcely visible because of the high penetrating power of the rays used. The photographic plate for the purpose is inclosed in an ordinary plate holder and the hand is laid on the holder next to the sensitized side.

475. The Fluorescope. — Soon after the discovery of X-rays it was found that certain fluorescent substances, like platino-barium-cyanide, and calcium tungstate, become luminous under the action of X-rays. This fact has been turned to account in the construction of a *fluorescope* (Fig. 393), by means of which shadow pictures of concealed objects become visible. An opaque screen is covered on one side with the fluorescent substance; this screen fits into the larger end of a box blackened inside, and having at the other end an opening adapted to fit closely around the eyes, so as to exclude all outside light. When an ob-

Fig. 393

ject, such as the hand, is held against the fluorescent screen and the fluorescope is turned toward the Roentgen tube, the bones are plainly visible as darker objects than the flesh because they are more opaque to X-rays. The beating heart may be made visible in a similar manner.

476. Radioactivity. — Henri Becquerel of Paris discovered in 1896 that a double sulphate of potassium and uranium emits radiations which affect a photographic plate in the same way as the X-rays. All substances which emit radiations of this character are said to be *radioactive.* The principle ones are compounds of uranium, polonium, actium, and thorium.

In 1898, M. and Mme. Curie by chemical methods separated from pitchblende, an ore containing uranium, three substances each more highly radioactive than uranium; these were polonium, actium, and radium. Pure radium has not been obtained ; it is used in investigations in the form of a chloride or bromide, and in that form its radioactivity is more than a million times greater than that of the pitchblende from which it is derived. Its emanations excite strong fluorescence in some substances; their action on the human body is to produce sores difficult to heal. Radium is a very unstable substance, tending to disintegrate into other things. During these changes large quantities of energy in the form of heat are given off, a gram of radium yielding 100 calories of heat per hour. It has been calculated that this emission of energy will continue for a period of over 2600 years before exhaustion is reached.

477. The Electron Theory of Matter. — Facts revealed in the study of electric charges through high vacuum tubes by Crookes, J. J. Thomson, and others, along with the

revelations of radioactive substances, make it certain that the atom of chemistry is a compound and very complex in structure. By methods too complex to describe here, Thomson has seemingly shown that the ultimates of matter are minute particles, variously called *corpuscles* or *electrons*. These carry negative charges of electricity, and revolve about one another in very intricate orbits, the number of electrons and the character of their motions determining the nature of the atom which they compose, whether it is one of gold, lead, hydrogen, or what not. Each electron is calculated to be $\frac{1}{10^{13}}$ part of a centimeter in diameter, 700 of them making up an atom of hydrogen, 15,000 an atom of sodium, 100,000 an atom of mercury, and 160,000 an atom of radium, the weight of the atom being governed by the number of electrons composing it. The empty space in an atom is 10^{10} times greater than the space filled by the electron. There remains these mysteries to be solved: What are electrons? What does it mean to say that they are negative electric charges? What are positive electric charges? What is electricity? Can we hope ever to control the groupings of these electrons and produce any kind of matter at will, thereby realizing the dream of the ancient alchemists? Will it ever be possible to release the vast stores of energy locked up in the atom for the use of mankind when other stores of energy have been exhausted?

Madame Marie Sklodowska Curie was born in Warsaw in 1867. She imbibed the spirit of scientific research from her father, a distinguished physicist and chemist. In 1895 she married Professor Curie of the University of Paris. Three times she has been awarded the Gegner prize by the French Academy for her valuable contributions to the world's knowledge of the magnetic properties of iron and steel and for her discoveries in radioactivity. In 1903 and again in 1911 the Nobel prize was awarded her. In January of 1911 she failed only by two votes of election to membership in the French Academy of Sciences, being defeated by Branley, the inventor of the coherer used in the Marconi system of wireless telegraphy.

CHAPTER XIV

DYNAMO-ELECTRIC MACHINERY

I. DIRECT CURRENT MACHINES

478. A Dynamo-Electric Machine converts mechanical energy into the energy of currents of electricity. It is a direct outgrowth of the discoveries of Faraday about induced electromotive forces and currents in 1831. It is an essential part of every system, steam or hydroelectric, for electric lighting, the transmission of electric power, electric railways, electric locomotives, electric smelting, electrolytic refinement of metals, electric train lighting, the charging of storage batteries, and for every other use to which large electric currents are applied.

Every dynamo-electric machine has three essential parts: 1. The *field magnet* to produce a powerful magnetic field. 2. The *armature*, a system of conductors wound on an iron core, and revolving in the magnetic field in such a manner that the magnetic flux through these conductors varies continuously. 3. The *commutator*, or the *collecting rings* and the *brushes*, by means of which the machine is connected to the external circuit. If the magnetic field is produced by a permanent magnet, the machine is called a *magneto;* if by an electromagnet, the machine is a *dynamo*. They are both often called *generators*.

479. Ideal Simple Dynamo.—Suppose a single loop of wire to revolve between the poles of a magnet (Fig. 394)

in the direction of the arrow and around a horizontal axis. The light lines indicate the magnet flux running across from *N* to *S*. In the position of the loop drawn in full lines it incloses the largest possible magnetic flux or lines of force, but as the flux inclosed by the coil is not changing, the induced E. M. F. is zero. When it has rotated forward a quarter of a turn, its plane will be parallel to the magnetic flux, and no lines of force will then pass through it. During this quarter turn the decrease in the magnetic flux threading through the loop generates a direct E. M. F.; and if the rotation is uniform, the *rate of decrease* of flux through the loop increases all the way from the first position to the one shown by the dotted lines, where it is a maximum. The arrows on the loop show the direction of the E. M. F. During the next quarter turn there is an increase of flux through the loop, but it runs through the loop in the opposite direction because the loop has turned over; this is equivalent to a continuous decrease in the original direction, and therefore the direction of the induced E. M. F. around the loop remains the same for the entire half turn, and the E. M. F. again becomes zero when the half turn is completed. After the half turn, the conditions are all reversed and the E. M. F. is directed the other way around the loop. If the loop is part of a closed circuit, the current through it reverses twice every revolution.

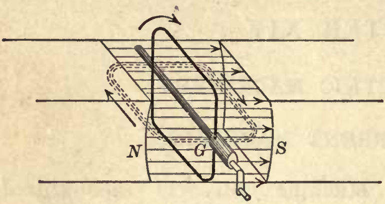


Fig. 394

480. The Commutator. — When it is desired to convert the alternating currents flowing in the armature into a

current in one direction through the external circuit, a special device called a *commutator* is employed. For a single coil in the armature, the commutator consists of two parts only. It is a split tube with the two halves, *a* and *b*, insulated from each other and from the shaft *S* on which they are mounted (Fig. 395). The two ends of the coil are connected with the two halves of the tube. Two brushes, with which the external circuit *L L* is connected, bear on the commutator, and they are so placed that they exchange contact with the two commutator segments at the same time that the current reverses in the coil. In this way one of the brushes is always positive and the other negative, and the current flows in the external circuit from the positive brush back to the negative, and thence through the armature to the positive again.

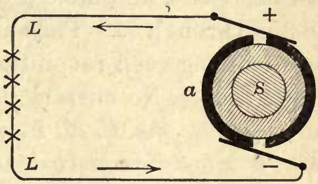


Fig. 395

481. The Gramme Ring. — The use of a commutator with more than two parts is conveniently illustrated in connection with the *Gramme ring*. This armature has a core made either of iron wire, or of thin disks at right angles to the axis of rotation. The iron is divided for the purpose of preventing induction currents in it, which waste energy. The relation of the several parts of the machine is illustrated by Fig. 396. A number of coils are wound in one direction and are all joined in series. Each junction

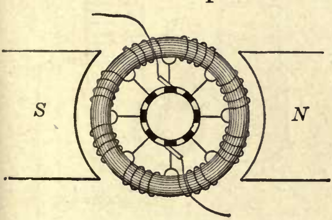


Fig. 396

between coils is connected with a commutator bar. Most of the magnetic flux passes through the iron ring from the north pole side to the south pole; hence, when a coil is in the highest position in the figure, the maximum flux passes through it; as the ring rotates, the flux through the coil decreases, and after a quarter of a revolution there is no flux through it. The current through each coil reverses twice during each revolution, exactly as in the case of the single loop. No current flows entirely around the armature, *because the E. M. F. generated in one coil at any instant is exactly counterbalanced by the E. M. F. generated in the coil opposite.* But when the external circuit connecting the brushes is closed, a current flows up on both sides of the armature. The current has then two paths through the armature, and one brush is constantly positive and the other negative.

482. The Field Magnet. — The magnetic field in dynamos is produced by a large electromagnet excited by the cur-

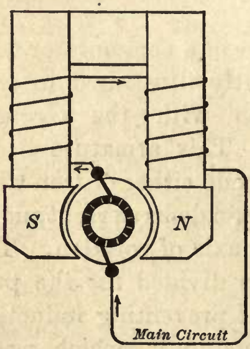


Fig. 397

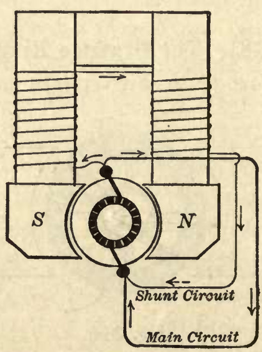


Fig. 398

rent flowing from the armature; this current is led, either wholly or in part, around the field-magnet cores. When the

entire current is carried around the coils of the field magnet, the dynamo is said to be *series wound* (Fig. 397). When the field magnet is excited by coils of many turns of fine wire connected as a shunt to the external circuit, the dynamo is said to be *shunt wound* (Fig. 398). A combination of these two methods of exciting the field magnet is called *compound winding* (Fig. 399). The residual magnetism remaining in the cores is sufficient to start the machine. The current thus produced increases the magnetic flux through the armature and so increases the E. M. F.

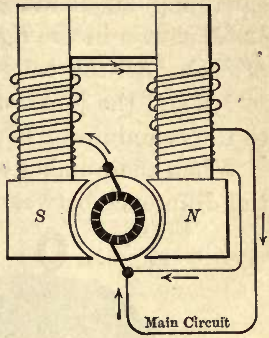


Fig. 399

483. The Drum Armature.—This very useful form of armature is shown at *A* in Fig. 400. It consists of an

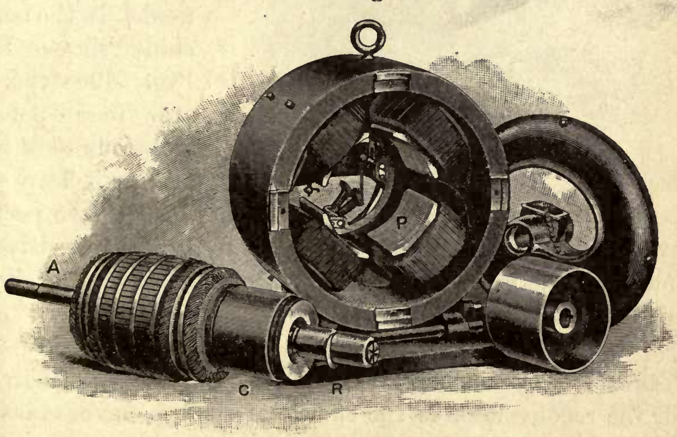


Fig. 400

iron core of laminated disks, in which are cut a series of grooves parallel to the shaft, and coils wound in them at equal angular distances around the circumference. (The *bands* shown in the figure serve only to keep the coils in place.) All the coils of the armature may be joined in series, and the junctions between them are then connected to the commutator bars *C*, as in the Gramme ring.

When the number of coils is twenty or more, the potential difference between the brushes never drops to zero, as it does in the case of a single coil (§ 479), but it remains nearly constant. To reduce the rate of rotation of the armature, field magnets of four, six, eight, or more poles are used. In the machine shown in Fig. 400 there are four poles and four sets of brushes. Two of the brushes are positive and two negative; the two positive brushes are connected in parallel to form one positive, and the same is true of the two negative ones. Fig. 401 is the assembled machine ready to run.

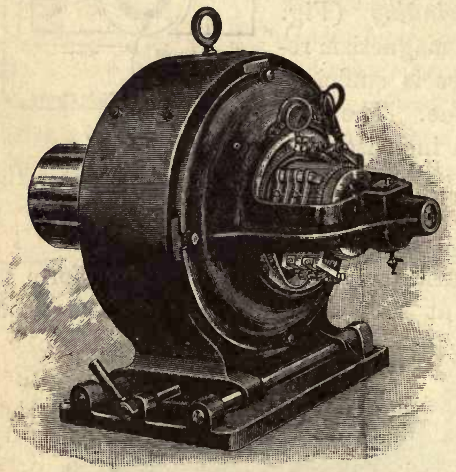


Fig. 401

484. The Electric Motor. — The *electric motor* is a machine for the reconversion of the energy of electric currents into mechanical power.

In the electric automobile the motor is driven by currents from a storage battery. In the electric street car it derives its current and power from a trolley, a third rail, or from conductors fixed in a slotted conduit under the pavement, all of them leading back to a power house or a substation. The electric motor is extensively used for small power as well as for large units. Witness the use of electric fans, electric coffee grinders, sewing machine motors, and electrically driven bellows for pipe organs on one hand, and on the other the electric drive for large fans to ventilate mines and buildings, electric elevators, and electrically driven mills and factories.

An electric motor for direct currents is constructed in the same manner as a generator. In fact, any direct current generator may be used as a motor. A study of the magnetic field resulting from the interaction of the field of the field magnet and that of a single loop carrying an electric current will make it clear that such a loop has a tendency to rotate. In Fig. 402 the field between unlike poles is distorted by a current through a loop of wire, which came up through one of the holes shown and went down through the other. These lines of force are under tension and tend to straighten out; there is therefore a magnetic stress acting on the loop and tending to turn it counter-clockwise. If the loop is allowed to rotate in the direction of this magnetic effort between the field and the loop, the loop is an armature and work is done by the machine as a motor. But if the loop is rotated clockwise by me-

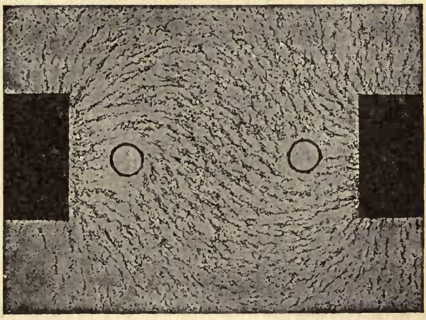


Fig. 402

chanical means, it turns against the magnetic effort acting on it, and work must be done against the resistance of this magnetic drag. The loop is then the armature of a generator.

II. ALTERNATORS AND TRANSFORMERS

485. The Alternator. — If the brushes *A* and *B* of a dynamo bear on two continuous rings mounted on the shaft (Fig. 403), instead of on a commutator, the current in the external circuit *WW* will alternate or reverse, as it does in an armature coil, every time the armature turns through the angular distance from one pole to the next.

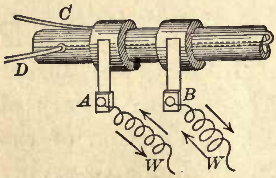


Fig. 403

A complete series of changes in the current and E. M. F. in both directions takes place while the armature is turning from one pole to the next one of the same name. Such a series of changes is called a *cycle*. The *frequency* is equal to the product of the number of pairs of poles on the field magnet and the number of rotations per second. Frequencies are now restricted between the limits of about 25 and 60 cycles per second. Multipolar machines are used to avoid excessive speed of rotation.

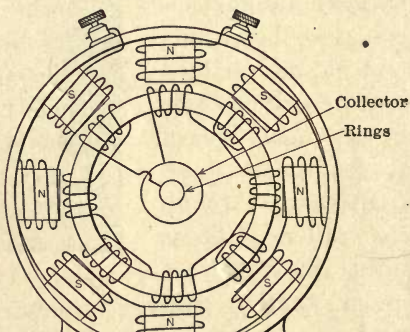


Fig. 404

Figure 404 is a diagram of an alternator with a stationary field outside and an armature rotating with the shaft. The field is excited by a direct current machine. The armature coils are reversed in winding from one field pole N to the next S, they are joined in series, and the terminals are brought out to rings on the shaft. The brushes bearing on these rings lead to the external circuit.

486. Transformers. — A *transformer* is an induction coil with a primary of many turns of wire and a secondary of a smaller number, both wound around a divided iron core forming a closed magnetic circuit; that is, one magnetic circuit is interlinked with two electric circuits (Fig. 405). A transformer is employed with alternating currents either to step down from a high E. M. F. to a low one, or the reverse. The two electromotive forces are directly proportional to the number of turns of wire in the two coils. For example, to reduce a 2000-volt current to a 100-volt current, there must be 20 turns in the primary to every one in the secondary. Both coils are wound on the same iron core, and are as perfectly insulated from each other as possible. The iron serves as a path for the flux of magnetic induction, and all the lines of force produced by either coil pass through the other, except for a small amount of "magnetic leakage." When the secondary is open, the transformer acts simply as a "choke coil"; that is, the self-induction of the primary is so large that only sufficient current is transmitted to magnetize the iron and to furnish the small amount of

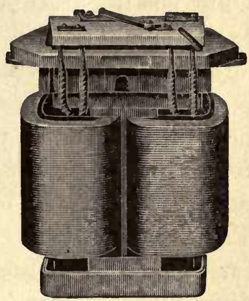


Fig. 405

energy lost in it. The counter-E. M. F. of self-induction is then nearly equal to the E. M. F. impressed from without. But when the secondary is closed, the self-induction is suppressed to the extent that the transformer automatically adjusts itself to the condition that the energy in the secondary circuit lacks only a few per cent of the energy absorbed by the primary from the generator.

487. Transformers in a Long-distance Circuit. — The utility of the transformer lies in its use to secure high voltage for transmission and low voltage for lighting and power. Only small currents can be transmitted over distances exceeding a few hundred feet without excessive heat losses on account of the resistance of the conductors. To transmit power while still keeping the current small, the electric pressure, that is, the number of volts, must be increased, for power transmitted in watts is proportional to the product of the number of volts and the number of amperes. Transformers are in actual use on long-distance circuits for raising the voltage to 100,000 or more volts potential difference between the main long-distance wires. Fig. 406 is a diagram showing a transformer system for long-

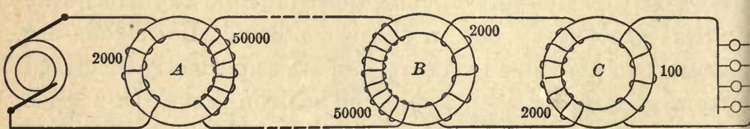
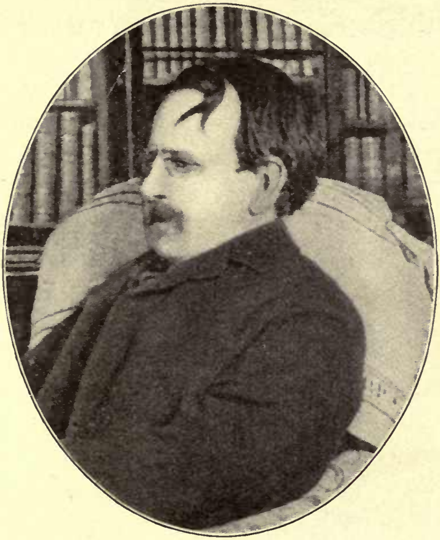


Fig. 406

distance power transmission. The first transformer *A* raises the potential difference from 2000 volts to 50,000 volts. The long distance transmission takes place at this voltage to the second transformer *B*, which steps down from 50,000 to 2000 volts for local transmission within



Sir Joseph John Thomson was born near Manchester, England, in 1856. He received his early training at Owens College, and acquired there some knowledge of experimental work in the laboratory of Balfour Stewart. At the age of twenty-seven he was appointed to the Cavendish professorship at the University of Cambridge, a position made famous by Maxwell and Rayleigh. The wisdom of the appointment was soon proved; for shortly after, Thomson began a series of experiments on the conduction of electricity through gases, culminating in the discovery of the "electron," out of which has developed the electron theory of matter.

the limits of a city. The third transformer *C* steps down further from 2000 to 100 volts for house service for lighting, fan motors, electric cooking, electric flat irons, etc.

III. ELECTRIC LIGHTING

488. The Carbon Arc. — In 1800 Sir Humphry Davy discovered that when two pieces of charcoal suitably connected to a powerful voltaic battery were brought into contact at their ends and were then separated a slight distance, brilliant sparks passed between them. No mention was made of the *electric arc* until 1808. With a battery of 2000 cells and the carbons in a horizontal line, they could be separated several inches, while the current was conducted across in the form of a curved flame or *arc.* Hence the name *electric arc* given to this form of electric lighting.

Fig. 407

Dense compressed or molded carbon rods are now used, and when they are separated a slight distance they are heated to an exceedingly high temperature, and the current from a dynamo continues to pass across through the heated carbon vapor. The ends of the carbon rods in the open air are disintegrated, a depression or "crater" forming in the positive and a cone on the negative (Fig. 407). Most of the light of the open arc comes from the bottom of this crater, the temperature of which Violle has estimated to be 3500° C. The arc light may be produced in a vacuum. The intense heat is not, there-

fore, generated by combustion. It is the energy of the current converted into heat by the resistance of the arc.

489. The Open and the Inclosed Arc. — To keep the carbon rods from burning away too rapidly, modern arc lamps are mostly of the "inclosed arc" type. The lower carbon and a part of the upper one are inclosed in a small glass globe, which is air-tight at the bottom, but allows the upper carbon to slip through a check-valve at the top (Fig. 408). Soon after the arc begins to burn, the oxygen in the globe is absorbed and the arc is then inclosed in an atmosphere of nitrogen from the air and of carbon monoxide from the incomplete combustion of the carbon. The inclosed arc is longer than the open arc, and the E. M. F. is about 80 volts instead of 50 as required by the open arc; but the current for the inclosed arc is smaller than for the open arc. The carbons for the inclosed arc last about ten times as long as in the open air.

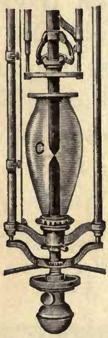


Fig. 408

490. Other Arc Lights. — Other arc lamps are now in commercial use in which the light comes chiefly from the incandescent stream between the electrodes. They have a higher efficiency than the carbon arc. In the "metallic arc" powdered *magnetite* in an iron tube is used for one electrode and a block of copper for the other. The arc flame is very white and brilliant, the light coming from the luminous iron vapor.

"Flaming arcs" are made by the use of a positive electrode impregnated with salts of calcium. The light from the flaming arc is yellow, and is adapted to outdoor illumination only.

491. The Incandescent Lamp. — The heat and light in an incandescent lamp are due to the simple resistance of a conducting filament inclosed in an exhausted glass globe (Fig. 409). The ends of the filament are connected through the glass by means of short pieces of platinum wire. Platinum is used because its coefficient of expansion is about the same as that of glass; and so, when the lamp becomes hot in use, it neither leaks air around the wires nor cracks.

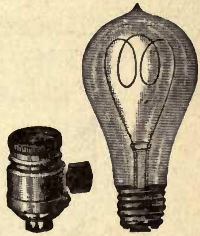


Fig. 409

The carbon filament is usually made from cellulose obtained from cotton. The temperature to which a carbon filament can be raised is limited by the tendency of the carbon to disintegrate at high temperatures. The carbon thrown off rapidly reduces the thickness of the filament and blackens the globe. The useful life of a carbon filament is from 600 to 800 hours.

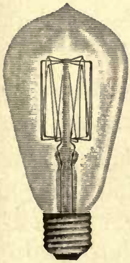


Fig. 410

In recent years filaments have been made of the rare metals, osmium, tantalum, and tungsten. The tungsten lamp (Fig. 410) is rapidly displacing the carbon lamp because of its higher efficiency, in spite of the fact that it is much more fragile.

The ordinary commercial unit for the carbon filament is the 16-candle power incandescent lamp. On a 110-volt circuit it takes about 0.5 ampere. Since the power in watts consumed is EI, this lamp consumes about 55 watts, or 3.5 watts per candle power. The tungsten 25-watt lamp gives 20 candle power, and the 40-watt lamp 32 candle power, or 1.25 watts per candle.

492. Incandescent Lamp Circuits. — Incandescent lamps are connected in parallel between the mains in a building. These mains lead either directly to a dynamo (Fig. 411),

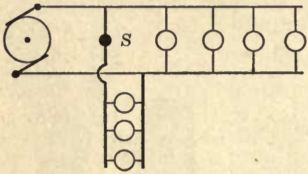


Fig. 411

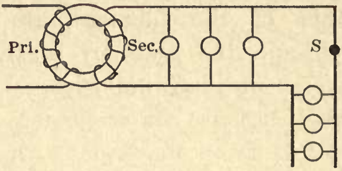


Fig. 412

or to the low voltage side of a transformer in the case of alternating currents (Fig. 412). Single lamps are turned off usually by the key in the socket (Fig. 409), and groups of lamps by a switch S.

IV. THE ELECTRIC TELEGRAPH

493. The Electric Telegraph is a system of transmitting messages by means of simple signals through the agency of an electric current. Its essential parts are the *line*, the *transmitter* or *key*, the *receiver* or *sounder*, and the *battery*.

494. The Line is an iron, copper or phosphor-bronze wire, insulated from the earth except at its ends, and serving to connect the signaling apparatus. The ends of this conductor are connected with large metallic plates, or with gas or water pipes, buried in the earth. By this means the earth becomes a part of the electric circuit containing the signaling apparatus.

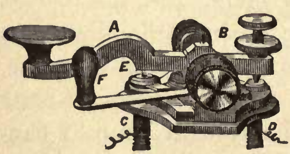


Fig. 413

495. The Transmitter or Key (Fig. 413) is merely a current

interrupter, and usually consists of a brass lever *A*, turning about pivots at *B*. It is connected with the line by the screws *C* and *D*. When the lever is pressed down, a platinum point projecting under the lever is brought in contact with another platinum point *E*, thus closing the circuit. When not in use, the circuit is left closed, the switch *F* being used for that purpose.

496. The Receiver or Sounder (Fig. 414) consists of an electromagnet *A* with a pivoted armature *B*. When the circuit is closed through the terminals *D* and *E*, the armature is attracted to the magnet, producing a sharp click. When the circuit is broken, a spring *C* causes the lever to rise and strike the back stop with a lighter click.

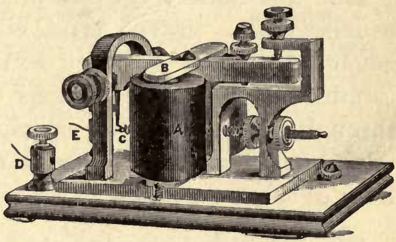


Fig. 414

497. The Relay. — When the resistance of the line is large, the current is not likely to be strong enough to operate the sounder with sufficient energy to render the signals distinctly audible. To remedy this defect, an electromagnet, called a *relay* (Fig. 415), whose helix *A* is composed of many turns of fine wire, is placed in the circuit by means of its terminals *C* and *D*. As its armature moves to and

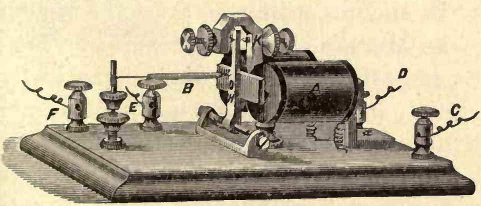


Fig. 415

fro between the points at K, it opens and closes a second and shorter circuit through E and F, in which the sounder is placed. Thus the weak current, through the agency of the relay, brings into action a current strong enough to do the necessary work.

498. **The Battery** consists of a large number of cells, usually of the gravity type, connected in series. It is generally divided into two sections, one placed at each terminal station, these sections being connected in series through the line. The principal circuits of the great telegraph companies are now worked by means of currents from dynamo machines.

499. **The Signals** are a series of sharp and light clicks separated by intervals of silence of greater or less duration, a short interval between the clicks being known as a "dot," and a long one as a "dash." By a combination of "dots" and "dashes," letters are represented and words are spelled out.

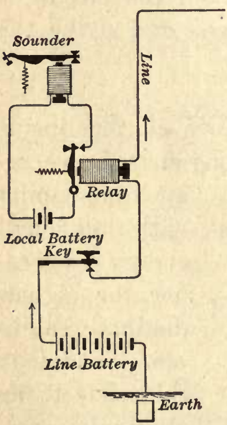


Fig. 416

500. **The Telegraph System** described in the preceding sections is known as Morse's, from its inventor. Figure 416 illustrates diagrammatically the instruments necessary for one terminal station, together with the mode of connection. The arrangement at the other end of the line is an exact duplicate of this one, the two sections of the battery being placed in the line, so that the negative pole of one and the positive of the other are connected with the earth.

At intermediate stations the relay and the local circuit are connected with the line in the same manner as at a terminal station.

501. The Electric Bell (Fig. 417) is used for sending signals as distinguished from messages. Besides the gong, it contains an electromagnet, having one terminal connected directly with a binding-post, and the other through a light spring attached to the armature (shown on the left of the figure) and a contact screw, with another binding-post. One end of the armature is supported by a stout spring, or on pivots, and the other carries the bent arm and hammer to strike the bell. Included in the circuit are a battery and a push-button *B*, shown with the top unscrewed in Fig. 418.

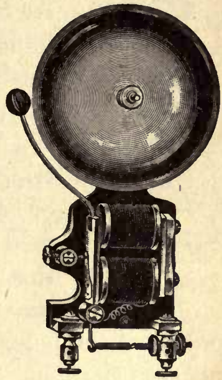


Fig. 417

When the spring *E* is brought into contact with *D* by pushing *C*, the circuit is closed, the electromagnet attracts the armature, and the hammer strikes the gong. The movement of the armature opens the circuit by breaking contact between the spring and the point of the screw; the armature is then released, the retractile spring at the bottom carries it back, and contact is again established between the spring and the screw. The whole operation is repeated automatically as long as the circuit is kept closed at the push-button. A "buzzer" is an electric bell without the hammer and gong.

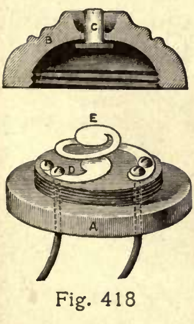


Fig. 418

V. THE TELEPHONE

502. The Telephone (Fig. 419) consists of a permanent magnet *O*, one end of which is surrounded by a coil of many turns of fine copper wire *b*, whose ends are connected with the binding-posts *t* and *t*. At right angles to the magnet, and not quite touching the pole within the coil is an elastic diaphragm or disk *a* of soft sheet-iron, kept in place by the conical mouthpiece *d*. If the instrument is placed in an electric circuit when the current is unsteady, or alternating in direction, the magnetic field due to the helix, when combined with that due to the magnet, alters intermittently the number of lines of force which branch out from the pole, thus varying the attraction of the magnet for the disk. The result is that the disk vibrates in exact keeping with the changes in the current.

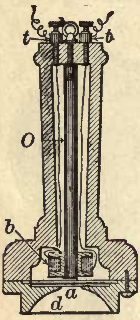


Fig. 419

503. The Microphone is a device for varying an electric current by means of a variable resistance in the circuit. One of its simplest forms is shown in Fig. 420. It consists of a rod of gas-carbon *A*, whose tapering ends rest loosely in conical depressions made in blocks of the same material attached to a sounding board. These blocks are placed in circuit with a battery and a telephone. While the current is passing, the least motion of the sounding board, caused either by sound waves or by any other means, such as the ticking of a

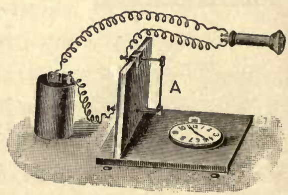


Fig. 420

watch, moves the loose carbon pencil and varies the pressure between its ends and the supporting bars. A slight increase of pressure between two conductors resting loosely one on the other lessens the resistance of the contact, and conversely. Hence, the vibrations of the sounding board cause variations in the pressure at the points of contact of the carbons, and consequently make corresponding fluctuations in the current and vibrations of the telephone disk.

504. The Solid Back Transmitter. — The varying resistance of carbon under varying pressure makes it a valuable material for use in telephone transmitters. Instead of the loose contact of the microphone, carbon in granules between carbon plates is now commonly employed.

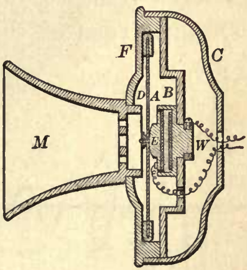


Fig. 421

The form of transmitter extensively used for long distance work is the "solid back" transmitter (Fig. 421). The figure shows only the essential parts in section, minor details being omitted. *M* is the mouthpiece, and *F* and *C* the front and back parts of the metal case. The aluminum diaphragm *D* is held around its edge by a soft rubber ring. The metal block *W* has a recess in front to receive the carbon electrodes *A* and *B*. Between them are the carbon granules. The block *E* is attached to the diaphragm and is insulated from *W* except through the carbon granules. The transmitter is placed in circuit by the wires connected to *W* and *E*.

Provision is made for an elastic motion of the diaphragm and the block *E*. Sound waves striking the diaphragm

cause a varying pressure between the plates and the carbon granules. This varying pressure varies the resistance offered by the granules and so varies the current. The transmitter is in circuit in the line with the primary of a small induction coil, the secondary being in a local circuit with the telephone receiver. The induced currents in the secondary have all the peculiarities of the primary current; and when they pass through a receiver, it responds and reproduces sound waves similar to those which disturb the disk of the transmitter.

VI. WIRELESS TELEGRAPHY

505. Oscillatory Discharges. — The discharge of any condenser through a circuit of low resistance is oscillatory. The first rush of the discharge surges beyond the condition of equilibrium, and the condenser is charged in the opposite sense. A reverse discharge follows, and so on, each successive pulse being weaker than the preceding, until after a few surges the oscillations cease. Figure 422 was made from a photograph of the oscillatory discharge of a condenser by means of a very small mirror, which reflected a beam of light on a falling sensitized plate. Such alternating surges of high frequency are called *electric oscillations*. Joseph Henry discovered long ago that the discharge of a Leyden jar is oscillatory.

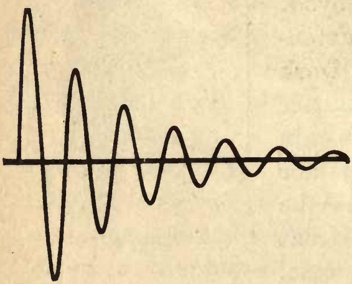


Fig. 422

506. Electric Waves. — In 1887–1888 Hertz made the discovery that electric oscillations give rise to electric

Heinrich Rudolf Hertz (1857–1894) was born in Hamburg, and was educated for a civil engineer. Having decided to abandon his profession, he went to Berlin and studied under Helmholtz, and later became his assistant. In 1885 he was appointed professor of physics at the Technical High School at Karlsruhe, and while there he discovered the electromagnetic waves predicted by Maxwell, who in the middle of the century had advanced the idea that waves of light are electromagnetic in character In 1889 he was elected professor of physics at Bonn, where he died at the age of thirty-seven. Electromagnetic waves are called Hertzian waves in his honor.

waves in the ether, which appear to be the same as waves of light, except that they are very much longer, or of lower frequency. They are capable of reflection, refraction, and polarization the same as light.

Evidence of these waves may be readily obtained by setting up an induction coil, with two sheets of tin-foil on glass, Q and Q', connected with the terminals of the secondary coil, and with two discharge balls, F and F', as shown in Fig. 423. So simple a device as a large picture

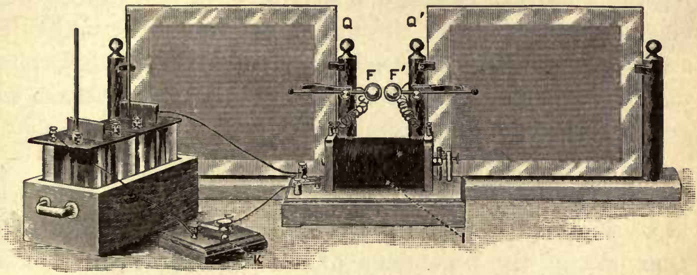


Fig. 423

frame with a conducting gilt border may be used to detect waves from the tin-foil sheets. If the frame has shrunken so as to leave narrow gaps in the miter at the corners, minute sparks may be seen in a dark room breaking across these gaps when the induction coil produces vivid sparks between the polished balls, F and F'. The plane of the frame should be held parallel with the sheets of tin-foil. The passage of electric waves through a conducting circuit produces electric oscillations in it, and these oscillations cause electric surges across a minute air gap.

507. The Coherer.—A very sensitive device for the detection of electric waves is the *coherer* (Fig. 424). When metallic filings are placed loosely between solid

electrodes in a glass tube they offer a high resistance to the passage of an electric current; but when electric oscillations are produced in the neighborhood of the tube, the resistance of the filings falls to so small a value that a single voltaic cell sends through them a current strong enough to work a relay (§ 497). If the tube is slightly jarred, the filings resume their state of high resistance. A slight discharge from the cover of an electrophorus (§ 398) through the filings lowers the resistance just as electric oscillations do. It is thought that minute sparks between the filings partially weld them together and make them conducting.

Fig. 424

508. Wireless Telegraph Set. — The connections and parts of a simple wireless telegraph set are shown in Fig. 425. One ball of the secondary of the induction coil is con-

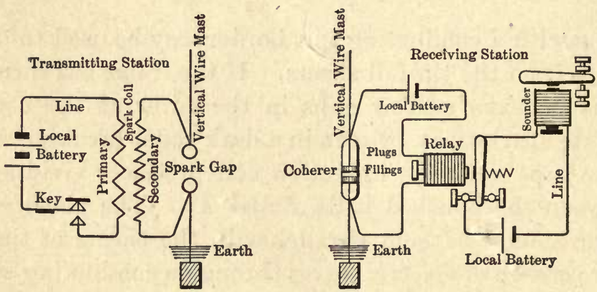


Fig. 425

nected to the earth and the other to a vertical wire mast for transmitting electric waves. At the receiving station a similar wire mast is connected to one end of a coherer which is joined in series with a battery and a relay. The

make and break circuit of the relay includes a sounder operated by another battery. When the transmitter and the receiver are both properly adjusted, the closing of the key at the sending station produces sparks at the spark gap of the secondary coil; the electric waves sent out by the vertical mast are received by the corresponding one at the receiving station, the coherer has its resistance lowered so that the battery works the relay, and the sounder responds. The sounder is usually made to tap the coherer for the purpose of restoring its sensitiveness for the reception of the next waves.

Wireless messages are transmitted further over the ocean than over the land. In fact the most conspicuous application of wireless telegraphy is between ships at sea, or between them and shore stations. It has proved of inestimable value in the timely assistance it has brought to disabled or sinking vessels. Ocean liners are in daily communication with other vessels or with maritime stations. Wireless systems of communication are now a part of the equipment of naval vessels. They may thus be kept in touch with one another and with the navy department of the governments they represent.

APPENDIX

I. GEOMETRICAL CONSTRUCTIONS

The principal instruments required for the accurate construction of diagrams on paper are the *compasses* and the *ruler*. For the construction of angles of any definite size the *protractor* (Fig. 426) can be used. There are, however, a number of angles, as 90°, 60°, and those which can be obtained from these by bisecting them and combining their parts, that can be constructed by the compasses and ruler alone.

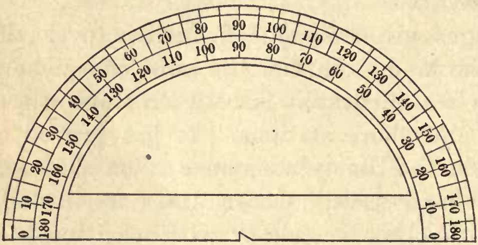


Fig. 426

A convenient instrument for the rapid construction of the angles 90°, 60°, and 30°, is a triangle made of wood, horn, hard rubber, or cardboard, whose angles are these respectively. Such a triangle may be easily made from a postal card as follows: Lay off on the short side of the card (Fig. 427) a distance a little less than the width, as *AB*. Separate the points of the compasses a distance equal to twice this distance. Place one point of the compasses at *B*, and draw an arc cutting the adjacent side at *C*.

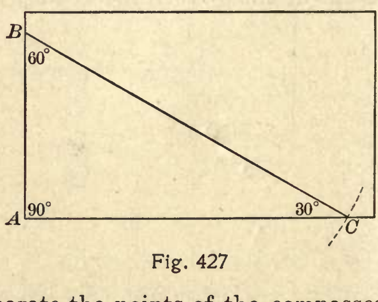


Fig. 427

Cut the card into two parts along the straight line *BC*. The part *ABC* will be a right-angled triangle, having the longest side twice as long as the shortest side, with the larger acute angle 60° and the smaller 30°. With this triangle and a straight edge the majority of the constructions required in elementary physics can be made.

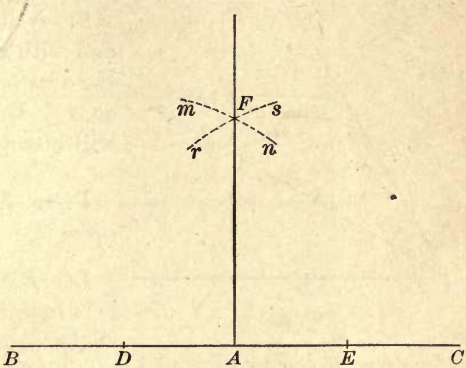


Fig. 428

Prob. 1. — *To construct an angle of 90°.*

Let *A* be the vertex of the required angle (Fig. 428). Through *A* draw the straight line *BC*. Measure off *AD*, any convenient distance; also make *AE* = *AD*. With a pair of compasses, using *D* as a center, and a radius longer than *AD*, draw the arc *mn*; with *E* as a center and the same radius, draw the arc *rs*, intersecting *mn* at *F*. Join *A* and *F*. The angles at *A* are right angles.

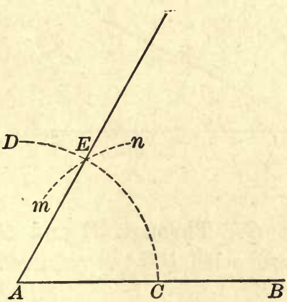


Fig. 429

Prob. 2. — *To construct an angle of 60°.*

Let *A* be the vertex of the required angle (Fig. 429), and *AB* one of the sides. On *AB* take some convenient distance as *AC*. With a pair of compasses, using *A* as a center and *AC* as a radius, draw the arc *CD*. With *C* as a center and the same radius, draw the arc *mn*, intersecting *CD* at *E*. Through *A* and *E* draw the straight line *AE*; this line will make an angle of 60° with *AB*.

PROB. 3. — *To bisect an angle.*

Let BAC be an angle that it is required to bisect (Fig. 430). Measure off on the sides of the angle equal distances, AD and AE. With D and E as centers and with the same radius, draw the arcs mn and rs, intersecting at F. Draw AF. This line will bisect the angle BAC.

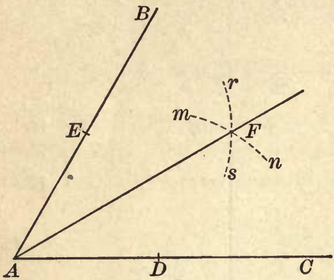


Fig. 430

PROB. 4. — *To make an angle equal to given angle.*

Let BAC be a given angle; it is required to make a second angle equal to it (Fig. 431). Draw DE, one side of the required angle. With A as a center and any convenient radius, draw the arc mn across the given angle. With D as a center and the same radius, draw the arc rs. With s as a center and a radius equal to the chord of

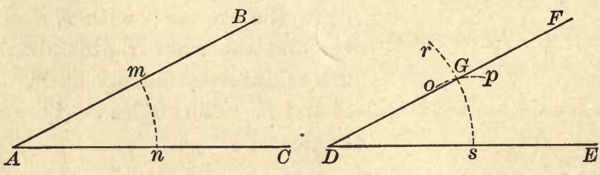


Fig. 431

mn, draw the arc op, cutting rs at G. Through D and G draw the line DF. This line will form with DE the required angle, as FDE.

PROB. 5. — *To draw a line through a point parallel to a given line.*

Let A be the point through which it is required to draw a line parallel to BC (Fig. 432). Through A draw ED,

cutting BC at D. At A make the angle EAG equal to EDC. Then AG or FG is parallel to BC.

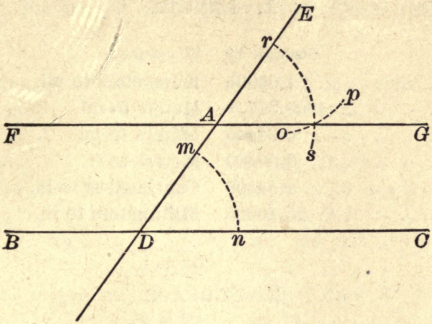


Fig. 432

PROB. 6. — *Given two adjacent sides of a parallelogram to complete the figure.*

Let AB and AC be two adjacent sides of the parallelogram (Fig. 433). With C as a center and a radius equal to AB,

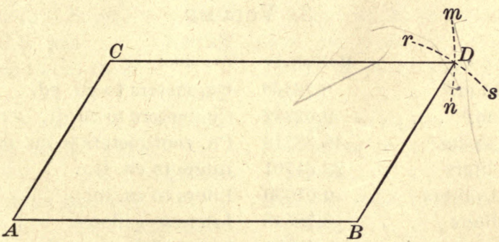


Fig. 433

draw the arc mn. With B as a center and a radius equal to AC, draw the arc rs, cutting mn at D. Draw CD and BD. Then $ABDC$ is the required parallelogram.

II. CONVERSION TABLES

1. Length

To reduce	Multiply by	To reduce	Multiply by
Miles to km.	1.60935	Kilometers to mi. . .	0.62137
Miles to m.	1609.347	Meters to mi. . . .	0.0006214
Yards to m.	0.91440	Meters to yd. . . .	1.09361
Feet to m.	0.30480	Meters to ft.	3.28083
Inches to cm.	2.54000	Centimeters to in. . .	0.39370
Inches to mm.	25.40005	Millimeters to in. . .	0.03937

2. Surface

To reduce	Multiply by	To reduce	Multiply by
Sq. yards to $m.^2$	0.83613	Sq. meters to sq. yd. . .	1.19599
Sq. feet to $m.^2$	0.09290	Sq. meters to sq. ft. . .	10.76387
Sq. inches to $cm.^2$	6.45163	Sq. centimeters to sq. in.	0.15500
Sq. inches to $mm.^2$.	645.163	Sq. millimeters to sq. in.	0.00155

3. Volume

To reduce	Multiply by	To reduce	Multiply by
Cu. yards to $m.^3$	0.76456	Cu. meters to cu. yd. . .	1.30802
Cu. feet to $m.^3$	0.02832	Cu. meters to cu. ft. . .	35.31661
Cu. inches to $cm.^3$	16.38716	Cu. centimeters to cu. in.	0.06102
Cu. feet to liters	28.31701	Liters to cu. ft.	0.03532
Cu. inches to liters . .	0.01639	Liters to cu. in. . . .	61.02337
Gallons to liters	3.78543	Liters to gallons . . .	0.26417
Pounds of water to liters .	0.45359	Liters of water to lb. .	2.20462

4. Weight

To reduce	Multiply by	To reduce	Multiply by
Tons to kgm.	907.18486	Kilograms to tons . .	0.001102
Pounds to kgm. . . .	0.45359	Kilograms to lb. . .	2.20462
Ounces to gm. . . .	28.34953	Grams to oz. . . .	0.03527
Grains to gm.	0.064799	Grams to grains . .	15.43236

5. Force, Work, Activity, Pressure

To reduce	Multiply by	To reduce	Multiply by
Lb.-weight to dynes, .	444520.58	Dynes to lb.-weight,	22496×10^{-10}
Ft.-lb. to kgm.-m.	0.138255	Kgm.-m. to ft.-lb. . . .	7.233
Ft.-lb. to ergs . . .	13549×10^{3}	Ergs to ft.-lb. . .	$0{\cdot}7381 \times 10^{-7}$
Ft.-lb. to joules . . .	1.3549	Joules to ft.-lb. . . .	0.7381
Ft.-lb. per sec. to H.P.	18182×10^{-7}	H.P. to ft.-lb. per sec. .	550
H.P. to watts	745.196	Watts to H.P.	0.001342
Lb. per sq. ft. to kgm. per m.^{2}	4.8824	Kgm. per m.^{2} to lb. per sq. ft.	0.2048
Lb. per sq. in. to gm. per cm.^{2}	70.3068	Gm. per cm.^{2} to lb. per sq. in.	0.01422

Calculated for $g = 980$ cm., or 32.15 ft. per sec. per sec.

6. Miscellaneous

To reduce	Multiply by	To reduce	Multiply by
Lb. of water to U.S. gal.	0.11983	U.S. gal. to lb. of water,	8.345
Cu. ft. to U.S. gal. . . .	7.48052	U.S. gal. to cu. ft. . .	0.13368
Lb. of water to cu. ft. at 4° C.	0.01602	Cu. ft. of water at 4° C. to lb.	62.425
Cu. in. to U.S. gal. . . .	0.004329	U.S. gal. to cu. in. . .	231
Atmospheres to lb. per sq. in.	14.69640	Lb. per sq. in. to atmospheres	0.06737
Atmospheres to gm. per cm.^{2}	1033.296	Gm. per cm.^{2} to atmospheres	0.000968
Lb.-degrees F. to calories,	252	Calories to lb.-degrees F.	0.003968
Calories to joules . . .	4.18936	Joules to calories . . .	0.2387
Miles per hour to ft. per sec.	1.46667	Ft. per sec. to miles per hour	0.68182
Miles per hour to cm. per sec.	44.704	Cm. per sec. to miles per hour	0.02237

III. MENSURATION RULES

Area of triangle	$= \frac{1}{2}$ (base $\times$ altitude).
Area of triangle	$= \sqrt{s(s-a)(s-b)(s-c)}$ where $s = \frac{1}{2}(a+b+c)$.
Area of parallelogram	= base $\times$ altitude.
Area of trapezoid	= Altitude $\times$ $\frac{1}{2}$ sum of parallel sides.
Circumference of circle	= diameter $\times$ 3.1416.
Diameter of circle	= { circumference $\div$ 3.1416. circumference $\times$ 0.3183.
Area of circle	= { diameter squared $\times$ 0.7854. radius squared $\times$ 3.1416.
Area of ellipse	= product of diameters $\times$ 0.7854.
Area of regular polygon	$= \frac{1}{2}$ (sum of sides $\times$ apothem).
Lateral surface of cylinder	= circumference of base $\times$ altitude.
Volume of cylinder	= area of base $\times$ altitude.
Surface of sphere	= { diameter $\times$ circumference. 4 $\times$ 3.1416 $\times$ square of radius.
Volume of sphere	= { diameter cubed $\times$ 0.5236. $\frac{4}{3}$ of radius cubed $\times$ 3.1416.
Surface of pyramid } Surface of cone }	$= \frac{1}{2}$ (circumference of base $\times$ slant height).
Volume of cone	$= \frac{1}{3}$ (area of base $\times$ altitude).

Lord Rayleigh (John William Strutt) was born at Essex in 1842, and graduated from Cambridge University in 1865. In 1884 he was appointed professor of experimental physics in that institution, and three years later he was elected professor of natural philosophy at the Royal Institution of Great Britain. His work is remarkable for its extreme accuracy. The discovery of argon in the atmosphere, while attempting to determine the density of nitrogen, was the result of a very minute difference between the result obtained by using nitrogen from the air and that from another source. Nearly every department of physics has been enriched by his genius. His treatise on Sound is one of the finest pieces of scientific writing ever produced. His determination of the electrochemical equivalent of silver and the electromotive force of the Clark standard cell are contributions of the first importance to modern electrical measurements.

IV. TABLE OF DENSITIES

The following tables gives the mass in grams of 1 $cm.^3$ of the substance: —

Agate	2.615	Human body	0.890
Air, at 0° C. and 76 cm. pressure	0.00129	Hydrogen, at 0° C. and 76 cm. pressure	0.0000896
Alcohol, ethyl, 90%, 20° C.	0.818	Ice	0.917
Alcohol, methyl	0.814	Iceland spar	2.723
Alum, common	1.724	India rubber	0.930
Aluminum, wrought	2.670	Iron, white cast	7.655
Antimony, cast	6.720	Iron, wrought	7.698
Beeswax	0.964	Ivory	1.820
Bismuth, cast	9.822	Lead, cast	11.360
Brass, cast	8.400	Magnesium	1.750
Brass, hard drawn	8.700	Marble	2.720
Carbon, gas	1.89	Mercury, at 0° C.	13.596
Carbon disulphide	1.293	Mercury, at 20° C.	13.558
Charcoal	1.6	Milk	1.032
Coal, anthracite	1.26 to 1.800	Nitrogen, at 0° C. and 76 cm. pressure	0.001255
Coal, bituminous	1.27 to 1.423	Oil, olive	0.915
Copper, cast	8.830	Oxygen, at 0° C. and 76 cm. pressure	0.00143
Copper, sheet	8.878	Paraffin	0.824 to 0.940
Cork	0.14 to 0.24	Platinum	21.531
Diamond	3.530	Potassium	0.865
Ebony	1.187	Silver, wrought	10.56
Emery	3.900	Sodium	0.970
Ether	0.736	Steel	7.816
Galena	7.580	Sulphuric Acid	1.84
German silver	8.432	Sulphur	2.033
Glass, crown	2.520	Sugar, cane	1.593
Glass, flint	3.0 to 3.600	Tin, cast	7.290
Glass, plate	2.760	Water, at 0° C.	0.999
Glycerin	1.260	Water, at 20° C.	0.998
Gold	19.360	Water, sea	1.027
Granite	2.650	Zinc, cast	7.000
Graphite	2.500		
Gypsum, crys.	2.310		

V. GEOMETRICAL CONSTRUCTION FOR REFRACTION OF LIGHT

The path of a ray of light in passing from one medium into another of different optical density is easily constructed geometrically. The following problems will make the process clear:

First.—A ray from air into water.—Let MN (Fig. 434) be the surface separating air from water, AB the incident ray at B, and BE the normal. With B as a center and a radius BA draw the arcs mn and Cs. With the same center and a radius $\frac{3}{4}$ of AB, ($\frac{4}{3}$ being the index for air to water), draw the arc Dr. Produce AB till it cuts the inner arc at D. Through D draw DC parallel to the normal EF, cutting the outer arc at C. Draw BC. This will be the refracted ray, because $\frac{AE}{CF} = \frac{4}{3}$, the index of refraction.

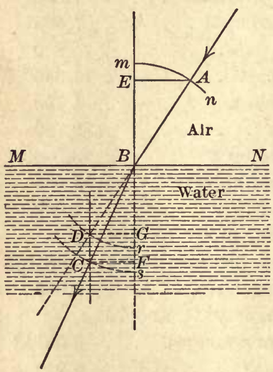


Fig. 434

When the ray passes from a medium into one of less optical density, then the ray is produced until it cuts the outer or arc of larger radius, and a line is drawn through this point parallel to the normal. The intersection of this line with the inner arc gives a point in the refracted ray which together with the point of incidence locates the ray.

If the incident angle is such that this line drawn parallel to the normal does not cut the inner arc, then the ray does not pass into the medium at that point but is totally reflected as from a mirror.

It is immaterial whether the arcs Dr and Cs are drawn in the quadrant from which the light proceeds, or, as in the figure, in the quadrant toward which it is going.

Second. — *Tracing a ray through a lens.* — Let MN represent a lens whose centers of curvature are C and C', and AB the ray to be traced through it (Figs. 435, 436). Draw the normal,

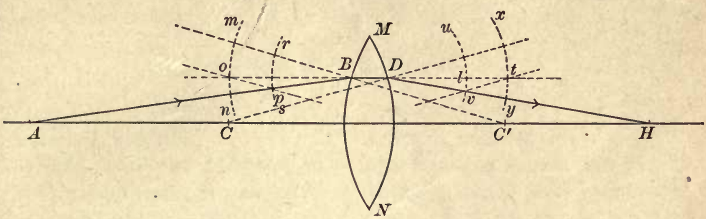


Fig. 435

$C'B$, to the point of incidence. With B as a center, draw the arcs mn and rs, making the ratio of their radii equal the index of refraction, $\frac{3}{2}$. Through p, the intersection of AB with rs, draw op parallel to the normal, $C'B$, and cutting mn at o. Through o and B draw oBD; this will be the path of the ray through the lens. At D it will again be refracted; to determine the amount, draw the normal CD and the auxiliary circles, xy and uv, as before. Through

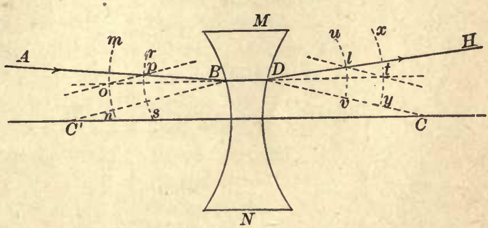


Fig. 436

the intersection of BD produced with xy, draw lt parallel to the normal CD, cutting uv at l. Through D and l draw DH; this will be the path of the ray after emergence.

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